ANL-EBR 1009

PLANCHON

THE EBR-II INHERENT SAFETY/OPERABILITY TESTING PROGRAM

PRESENTATION AT DOE-GT

ARGONNE NATIONAL LABORATORY
WEST
UNIVERSITY OF CHICAGO

February 18, 1988

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$$\frac{3600}{3}$$

THE EBR-II INHERENT SAFETY/OPERABILITY TESTING PROGRAM PRESENTATION AT DOE-GT

February 18, 1988

Agenda

		Actual		Bogie
(10 Min)	Introduction of ANL Presenters and Review of Agenda		D.W. Cissel	
(10 Min)	Introduction	9:34	G.H. Golden	9:40
(30 Min)	EBR-II Plant Testing in Support of IFR and EBR-II Operating Improvements	~~10:30~~	~~J.I.~~ Sackett BK	10:10
(40 Min)	Plant Diagnostics, Results and Applications	10:43	L.R. Monson	10 50
(10 Min)	*BREAK*			
(30 Min)	Plant Safety Tests and Implications		W.K. Lehto	11:30
(45 Min)	Plant Inherent Control Test; Implications for Advanced LMR Designs		H.P. Planchon	12:00
(10 Min)	*BREAK*			
(40 Min)	Discussion			12:40
(10 Min)	Summary		J.I. Sackett	

INTRODUCTION

G. H. Golden
EBR-II Division

INTRODUCTION

- Three basic accident categories of interest to designers and licensing bodies are LOHS, LOF, and TOP.

- Of far lower probability is occurrence of one of above and concurrent failure to scram — unprotected scenarios.

- If it can be demonstrated that a metal-fueled LMR can "survive" all three unprotected scenarios and be subsequently cooled by natural convection, it can probably be successfully argued that such an LMR plant would pose minimal public safety concern.

- If it can be further shown that the plant can be immediately restarted following any one of the above unprotected scenarios, the safety posture and economic features of the plant are enormously enhanced.

- It even seems possible to use the inherent feedback characteristics of a metal-fueled LMR together with advanced control and diagnostics technology to keep the plant online during and following a challenge to its control/protection system.

INTRODUCTION

(cont)

- The purpose of the EBR-II Inherent Safety/Operability Test (ISOT) program is to determine the degree of inherent safety and operational reliability obtainable with a metal-fueled LMR.

- The goal of the ISOT program is to demonstrate the immediate restartability of a metal-fueled LMR following an unprotected LOHS, LOF, or TOP.

OPERATOR INTERVENTION DURING EVENTS CANNOT MAKE it ~~g~~ degenerate to a problematic situation.

INTRODUCTION
(cont)

- Why, then, not just go ahead and do the unprotected TOP case in EBR-II?

- As an aside, there are really three sub-categories of TOP events, the familiar control rod withdrawal, but also primary pump run-up and sudden increase in power demand in the BOP.

- Focusing on the rod withdrawal (insertion in EBR-II), it is known that about half of the power reactivity decrement could be inserted from initial full-power conditions without taking the driver fuel above tech specs limits — this is about 1/5 of the worth of one control rod. As increasing amounts of reactivity would be added, there would be an increasing amount of fuel damage.

- The solution to this problem is to limit the total worth of control rods by controlling power by other means — this is the substance of the recently completed plant tests to be discussed shortly.

INTRODUCTION
(cont)

- But controlling power by other means requires the development of one or more control strategies.

- That is, the ability to conduct meaningful (limiting) rod withdrawal tests, as well as tests in the other two categories of unprotected TOPs, requires the development of a compatible control strategy.

- There are two other critically important reasons for work on a control strategy:

  - Control must be carefully designed not to override inherent safety characteristics of a plant, and

  - It must be designed to accommodate passively the malfunction of automatic controllers.

- The EBR-II ISOT program is thus a broad-based activity. The next presentation is a description of its various elements.

EBR-II PLANT TESTING IN SUPPORT OF IFR AND EBR-II OPERATING IMPROVEMENTS

J. I. Sackett
EBR-II Division

EBR-II PLANT TESTING IN SUPPORT OF IFR

AND

EBR-II OPERATING IMPROVEMENTS

EBR-II IS A TEST BED FOR:

1. **DEVELOPMENT OF APPROACHES TO CONTROL WHICH CAN ACCOMMODATE EQUIPMENT CONTROLLER OR OPERATOR FAILURE WITHOUT ENDANGERING THE SAFETY OF THE REACTOR (e.g. DO NOT REQUIRE SAFETY-SYSTEM ACTION).**

AND

2. **DEVELOPMENT OF DIAGNOSTIC AND CONTROL SYSTEM SOFTWARE TO SUPPORT INCREASINGLY SOPHISTICATED PLANT AUTOMATION OF EBR-II AND FUTURE LWRs AND LMRs.**

D. WHAT is ultimate CAPACITY of pumps
Ray Hunter.

EBR-II PLANT TESTING

THE NOVEMBER 1987 TESTS AT EBR-II WERE HIGHLY SUCCESSFUL IN DEMONSTRATING PROGRESS IN BOTH AREAS, SPECIFICALLY:

1. THE ABILITY TO EFFICIENTLY CONTROL REACTOR POWER THROUGH CHANGES IN REACTOR PRIMARY FLOW, SECONDARY SODIUM FLOW AND/OR STEAM FLOW WAS DEMONSTRATED,

2. SAFE RESPONSE OF THE REACTOR TO RAPID PRIMARY-PUMP RUNUP WAS DEMONSTRATED,

3. CONTROL FOR THE TESTS WAS TOTALLY AUTOMATED, A FIRST STEP TOWARD PLANT AUTOMATION

AND

4. THE SUCCESSFUL PERFORMANCE OF SEVERAL IMPORTANT DIAGNOSTIC AND DISPLAY SYSTEMS IN FOLLOWING PLANT TRANSIENTS WAS DEMONSTRATED.

Rank
How many
fuel Handling
ops?

EBR-II PLANT TESTING

OBSERVATIONS:

IMPROVEMENTS IN EBR-II OPERATION

1. OFF-NORMAL TESTING HAS PERMITTED INCREASINGLY THOROUGH CHARACTERIZATION OF EBR-II RESPONSE TO EQUIPMENT OR CONTROLLER FAILURE, A MAJOR ADVANTAGE IN DEFENSE OF EBR-II SAFETY TO OUTSIDE REVIEW GROUPS, e.g. THE NATIONAL ACADEMY OF SCIENCES REVIEW AND THE DOE TECHNICAL SAFETY APPRAISAL.

2. OFF-NORMAL TESTING IS LAYING THE BASIS FOR PLANT SIMPLIFICATION, e.g. USE OF THE AUXILIARY PUMP AS A FLOWMETER AND SIMPLIFICATION OF THE LOSS-OF-FLOW PROTECTION SYSTEM.

3. DEVELOPMENT AND QUALIFICATION OF DIAGNOSTIC AND CONTROL-SYSTEM SOFTWARE HAS SIGNIFICANT POTENTIAL FOR LESSENING THE COST OF OPERATION AND IMPROVING RELIABILITY, e.g. PROVIDING A MEASURE OF MIXED-MEAN REACTOR OUTLET TEMPERATURE IN THE ABSENCE OF AN OPERABLE TEMPERATURE SENSOR, RECHECKING THE FREQUENCY AND EXTENT OF INSTRUMENT CALIBRATION, PROTECTING FUEL-HANDLING EQUIPMENT AND AUTOMATING PLANT OPERATING FUNCTIONS.

Ray H.
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EBR-II PLANT TESTING

OBSERVATIONS:

FOR EBR-II AS A TEST BED,

1. TIES ARE BEING DEVELOPED WITH THE UNIVERSITY COMMUNITY AND NATIONAL LABS FOR CONTROL AND DIAGNOSTIC SYSTEM DEVELOPMENT (EG&G, ORNL, U of TENNESSEE, MIT, PENN STATE, U of ARIZONA, NORTH CAROLINA STATE, MICHIGAN AND MICHIGAN STATE, UCLA, TEXAS A&M). WAYNE STATE
2. TIES ARE BEING DEVELOPED WITH THE PRIVATE SECTOR FOR APPLICATION OF CONTROL AND DIAGNOSTIC SYSTEM TECHNOLOGY (EI INTERNATIONAL, NORTHEAST UTILITIES, EPRI, B&W USERS GROUP, GE, RI, WESTINGHOUSE).

EBR-II IS A POTENTIALLY IMPORTANT INTERFACE BETWEEN THE TWO GROUPS, TESTING AND GUIDING THE TECHNOLOGY TOWARD USEFUL APPLICATION. IT PROVIDES:

- ACCESS TO A COMPLETE LMR POWER PLANT,
- A CAPABILITY FOR ACTUAL OFF-NORMAL TESTING
- READY ACCESS TO PLANT DATA VIA A MODERN COMPUTER NETWORK
- AN EXPERIENCED ORGANIZATION TO SUPPORT DEVELOPMENT AND TESTING

<u>**EBR-II PLANT TESTING ELEMENTS**</u>

I. CONTROL STRATEGIES

H. P. PLANCHON, lead

II. ADVANCED SIMULATION

W. K. LEHTO, lead

III. DIAGNOSTICS

R. W. LINDSAY, R. W. KING, co-leaders

IV. PLANT AUTOMATION

L. J. CHRISTENSEN, W. H. PERRY, co-leaders

V. COMPUTER RELIABILITY

G. H. CHISHOLM, lead

THE FOLLOWING VIEWGRAPHS PRESENT OBJECTIVES AND ACCOMPLISHMENTS FOR EACH PLANT TESTING ELEMENT.

TEST ELEMENT I: DEVELOPMENT OF CONTROL STRATEGIES

OBJECTIVES:

1. **DEVELOP AND DEMONSTRATE APPROACHES TO LMR CONTROL THAT CAN POSSIBLY ACCOMMODATE CONTROLLER FAILURE OR OPERATOR ERRORS THAT RESULT IN:**

   - **INADVERTENT RUN-OUT OF A CONTROL ROD,**
   - **INADVERTENT RUN-DOWN OR RUN-UP OF PRIMARY FLOW**
   - **INADVERTENT RUN-DOWN OR RUN-UP OF SECONDARY SODIUM FLOW**
   - **INADVERTENT RUN-DOWN OR RUN-UP OF A FEEDWATER PUMP**
   - **INADVERTENT OPENING OR CLOSING OF TURBINE ADMISSION OR BYPASS VALVES**

   WITHOUT REQUIRING SAFETY-SYSTEM ACTION TO PROTECT THE REACTOR.

2. **DEVELOP AND DEMONSTRATE AN APPROACH TO CONTROL THAT PROVIDES A HIGH DEGREE OF OPERATING RELIABILITY AND SIMPLICITY BY:**

   - **LIMITING THE ADVERSE EFFECTS OF CONTROLLER MALFUNCTIONS OR OPERATOR ERRORS**
   - **ENHANCING LOAD FOLLOWING CAPABILITY WITHOUT REQUIRING RAPID CONTROL SYSTEM ACTION**
   - **FACILITATING AUTOMATION BY SAFELY ACCOMMODATING FAILURE OF CONTROL SYSTEM SOFTWARE.**

John LoScalso

X purpose

Automation ⟷ Simplicity

[ADD simplicity in safety systems]

TEST ELEMENT I: DEVELOPMENT OF CONTROL STRATEGIES (cont)

ACCOMPLISHMENTS:

FEASIBILITY OF CONTROLLING EBR-II THROUGH CHANGES IN PRIMARY, SECONDARY AND STEAM FLOW WITHOUT CONTROL-ROD MOTION HAS BEEN DEMONSTRATED.

BENIGN RESPONSE TO A RANGE OF CONTROLLER FAILURES HAS BEEN DEMONSTRATED.

- RUN-UP OR RUN-DOWN OF THE PRIMARY PUMPS
- RUN-UP OR RUN-DOWN OF THE SECONDARY PUMP
- RAPID LOSS OF STEAM PRESSURE

STILL TO BE ADDRESSED IS CONTROL-ROD RUN-OUT, TO BE DEMONSTRATED AS PART OF A CONTROL STRATEGY THAT LIMITS EXCESS REACTIVITY IN THE CONTROL RODS.

DESIGN CRITERIA FOR FOLLOW-ON PLANT DESIGNS TO ACHIEVE SIMILAR RESULTS ARE BEING DEVELOPED AND BENEFITS TO EBR-II ARE BEING ADDRESSED.

TEST ELEMENT II: ADVANCED SIMULATION DEVELOPMENT*

OBJECTIVES:

1. **DEVELOP AND DEMONSTRATE THE FEASIBILITY OF FASTER THAN REAL TIME, ON-LINE SIMULATION BY:**
   - **TRANSPORTING THE EBR-II SIMULATOR DSNP TO THE INEL CRAY X-MP/24**
   - **TRANSPORTING REAL-TIME PLANT DATA TO THE CRAY**
   - **INTERFACING THE CODE OUTPUT TO SUN GRAPHICS AND PROVIDING INTERACTIVE CAPABILITY WITH BOTH SIMULATED AND REAL-TIME PLANT DATA**
   - **RUNNING THE SIMULATION IN CONJUNCTION WITH PLANT TESTS TO PREDICT THE COURSE OF TRANSIENTS AND TAKE APPROPRIATE CONTROL ACTIONS**
2. **IMPROVE THE SPEED AND LOWER THE COST OF FASTER-THAN-REAL-TIME, ON-LINE SIMULATION BY:**
   - **PLANT TESTING TO SIMPLIFY MODELS TO INCREASE THE SPEED OF CALCULATION**
   - **STRUCTURING THE CODE TO TAKE ADVANTAGE OF THE VECTOR CAPABILITIES OF THE CRAY**

* **THIS WORK IS IN ANTICIPATION OF CONTINUED IMPROVEMENT IN COMPUTER HARDWARE CAPABILITY AND GREATLY REDUCED COST. IT ANTICIPATES A CONTROL/DIAGNOSTIC STRATEGY THAT USES FASTER-THAN-REAL-TIME PREDICTIVE CAPABILITY TO GUIDE CONTROL ACTIONS TO BE TAKEN IN THE COURSE OF PLANT MANEUVERING OR UPSETS. THE LINK BETWEEN THE EBR-II PLANT AND THE CRAY PROVIDES AN EXTREMELY FERTILE DEVELOPMENT ENVIRONMENT.**

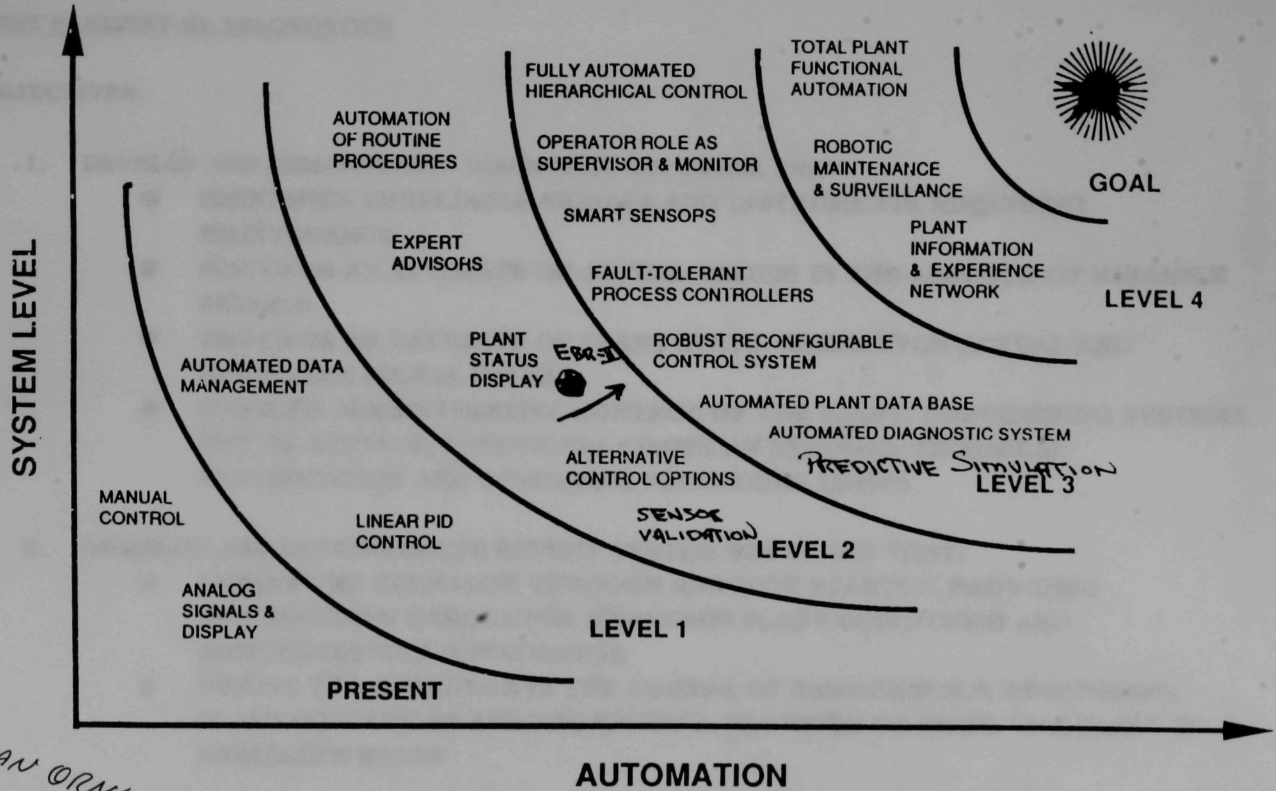
TEST ELEMENT II: ADVANCED SIMULATION DEVELOPMENT

ACCOMPLISHMENTS:

DSNP HAS BEEN SUCCESSFULLY IMPLEMENTED ON THE CRAY X-MP/24 AND A FULL PLANT SIMULATION OF THE EBR-II POWER PLANT IS RUNNING.

THE DATA LINK BETWEEN EBR-II AND THE INEL CRAY IS BEING ESTABLISHED; THE NEAR-TERM LINK WILL BE VIA THE ANL ETHERNET OVER PHONE LINES, TO BE UPGRADED TO A FIBER OPTICS LINK.

DEVELOPMENT OF GRAPHICS INTERFACING BETWEEN THE DSNP OUTPUT AND THE SUN SYSTEM HAS BEGUN.



This is an ORNL Vugraph. Overlaid with EBR II comments.

EVOLUTION OF NUCLEAR PLANT CONTROL AUTOMATION

A PHASED DEVELOPMENT PROGRAM APPROACH

TEST ELEMENT III: DIAGNOSTICS

OBJECTIVES:

1. **DEVELOP AND DEMONSTRATE DIAGNOSTIC SOFTWARE THAT:**
   - **IDENTIFIES UNRELIABLE SIGNALS AND INSTRUMENTS REQUIRING MAINTENANCE**
   - **PROVIDES AN ESTIMATE OF ACTUAL VALUES IN THE ABSENCE OF RELIABLE SIGNALS**
   - **PROVIDES AN ESTIMATE OF PLANT STATE, BASED UPON ACTUAL AND ESTIMATED SIGNAL VALUES**
   - **ENSURES ADMINISTRATIVE CONTROL OF THE PLANT, CONSIDERING SYSTEMS OUT OF SERVICE, FUNCTIONAL LIMITS ON SYSTEMS, TECHNICAL SPECIFICATION AND OPERATING PROCEDURE LIMITS**

2. **DEVELOP AND DEMONSTRATE EXPERT SYSTEM SOFTWARE THAT:**
   - **GUIDES THE OPERATOR THROUGH REACTOR STARTUP, PROVIDING INSTRUCTIONS BASED UPON MEASURED PLANT CONDITIONS AND ADMINISTRATIVE CONSTRAINTS**
   - **GUIDES THE OPERATOR IN THE COURSE OF EMERGENCIES, DIAGNOSING PLANT CONDITIONS AND PROPOSING A RESPONSE TO BRING THE PLANT TO A DESIRABLE STATE**

3. **DEVELOP AND DEMONSTRATE GRAPHIC DISPLAYS THAT:**
   - **INTEGRATE INFORMATION INTO A FORM EASILY RECOGNIZED BY THE OPERATOR**
   - **TIE DIAGNOSTIC AND CONTROL SYSTEMS TO PROVIDE A HIGH DEGREE OF AUTOMATION WHILE MAINTAINING OPERATOR AWARENESS OF ACTIONS TAKEN AND THEIR PURPOSE**

<u>**TEST ELEMENT III: DIAGNOSTICS (contd)**</u>

ACCOMPLISHMENTS:

A SOPHISTICATED COMPUTER NETWORK HAS BEEN ESTABLISHED FOR GATHERING, DISTRIBUTING, AND UTILIZING PLANT DATA FOR OPERATION AND DEVELOPMENT (SEE FIGURE 1)

A NUMBER OF DIAGNOSTIC SYSTEMS HAVE BEEN DEVELOPED AND EVALUATED, WITH THE MOST PROMISING BEING A PATTERN RECOGNITION METHOD CALLED THE SYSTEM STATE ANALYZER (SSA). SSA HAS BEEN TRANSPORTED TO NORTHEAST UTILITIES FOR TESTING AND IS BEING MARKETED BY EI INTERNATIONAL, WITH FURTHER DEVELOPMENT CONTINUING AT EBR-II.

A NUMBER OF DISPLAY METHODS HAVE BEEN EVALUATED, WITH THE MOST PROMISING BEING AN ICONIC DISPLAY OF HEAT AND MASS TRANSPORT IN THE SYSTEM, WITH A WIDE RANGE OF GRAPHIC PANELS ACCESSIBLE BENEATH THE MAIN DISPLAYS. THE SYSTEM IS IN OPERATION IN THE EBR-II CONTROL ROOM, WHERE IT IS UNDERGOING EVALUATION. (THE APPROACH HAS GENERATED CONSIDERABLE INTEREST; APPROXIMATELY 20 INDIVIDUAL ORGANIZATIONS HAVE VISITED FOR THE PURPOSE OF REVIEWING THESE SYSTEMS.)

A RUDIMENTARY EXPERT SYSTEM HAS BEEN DEVELOPED TO GUIDE THE OPERATOR THROUGH REACTOR STARTUP; ITS DEVELOPMENT IS CONTINUING.

EBR-II COMPUTER CAPABILITY

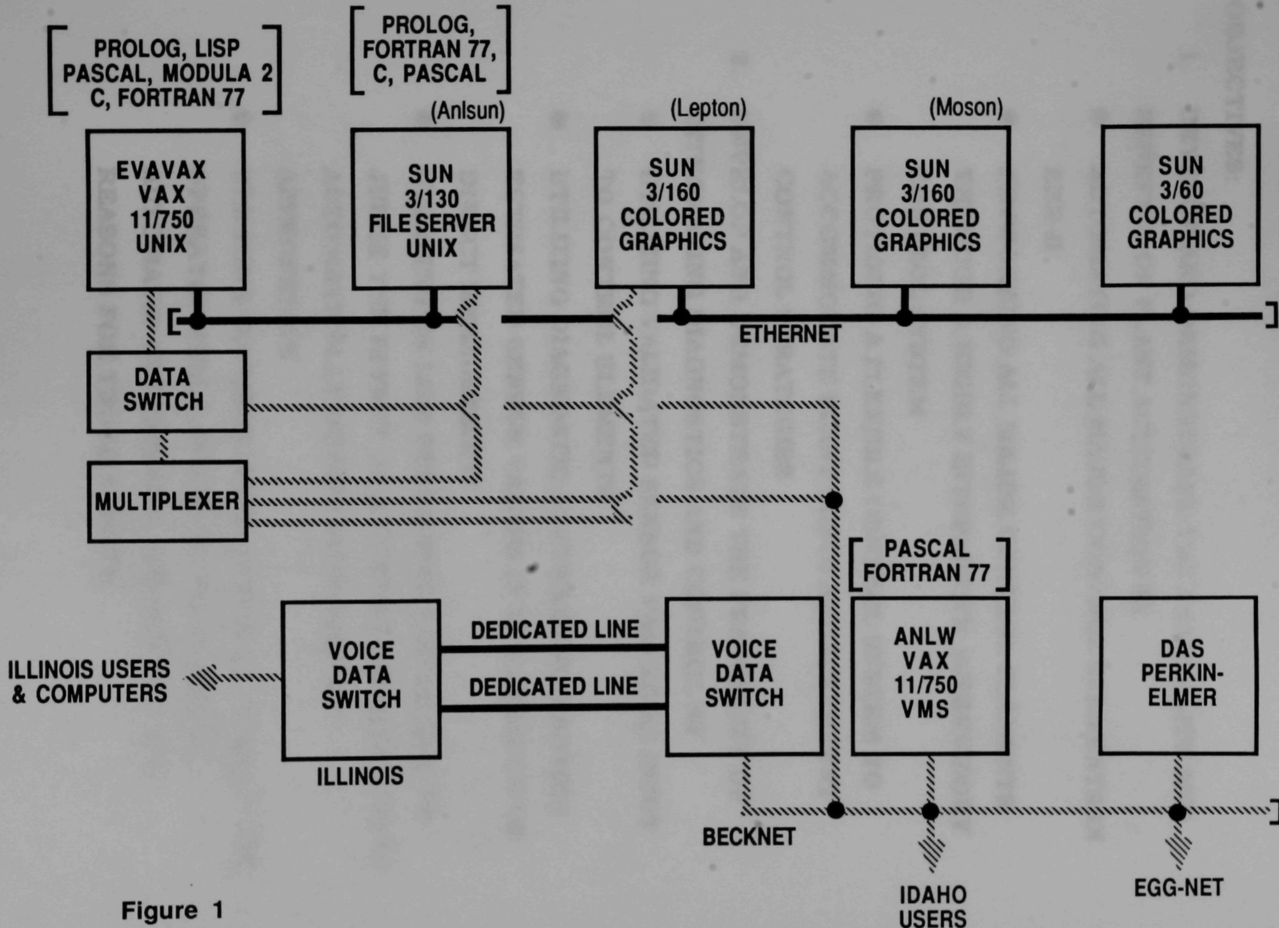


Figure 1

TEST ELEMENT IV: PLANT AUTOMATION

OBJECTIVES:

1. **DEVELOP AND DEMONSTRATE THE FEASIBILITY AND BENEFITS OF PLANT AUTOMATION BY**
   - **AUTOMATING ALL MAJOR CONTROL ELEMENTS IN EBR-II**
   - **NETWORKING ALL MAJOR CONTROL ELEMENTS THROUGH A HIGHLY INTERACTIVE SUPERVISORY CONTROL SYSTEM**
   - **PROVIDING A FLEXIBLE CONTROL SYSTEM TO ACCOMMODATE PLANT TESTS AND DIFFERENT CONTROL STRATEGIES**
2. **DEVELOP AND DEMONSTRATE THE FEASIBILITY OF INTEGRATING DIAGNOSTICS AND CONTROL BY**
   - **UTILIZING VALIDATED SENSOR VALUES AS INPUT TO CONTROL ELEMENTS**
   - **UTILIZING DIAGNOSTIC SOFTWARE TO PROVIDE ESTIMATED SENSOR VALUES IN THE ABSENCE OF DIRECT MEASUREMENT**
   - **UTILIZING ON-LINE PREDICTIVE SIMULATION TO JUDGE THE EFFECT OF A CONTROL ACTION AND TO AUTOMATICALLY MODIFY RESPONSE AS APPROPRIATE**
   - **UTILIZING SOPHISTICATED GRAPHICS TO KEEP THE OPERATOR FULLY AWARE OF PLANT STATE, AUTOMATIC CONTROLLER ACTIONS AND THE REASONS FOR THOSE ACTIONS**

TEST ELEMENT IV: PLANT AUTOMATION (contd)

ACCOMPLISHMENTS:

- ALL MAJOR CONTROLLERS IN THE PLANT HAVE BEEN REPLACED WITH MICROCOMPUTER-BASED UNITS CAPABLE OF ACCEPTING A VARIETY OF SOFTWARE.

    - PRIMARY POWER CONTROL
    - PRIMARY SYSTEM FLOW
    - SECONDARY FLOW
    - FEEDWATER SYSTEM
    - STEAM SYSTEM
    - AUXILIARY SYSTEMS

    THEY HAVE PROVEN TO BE VERY RELIABLE, REDUCING MAINTENANCE TIME.

- INDIVIDUAL CONTROLLERS HAVE BEEN NETWORKED THROUGH A SINGLE COMPUTER IN THE CONTROL ROOM FOR SPECIAL OPERATIONS. THE NOVEMBER 1987 TESTS WERE UNDER AUTOMATIC CONTROL.

- A SUPERVISORY CONTROL SYSTEM UTILIZING THE SUN GRAPHICS CAPABILITY IS BEING DEVELOPED AS THE NEXT STEP IN NETWORKING CONTROL ELEMENTS.

- INTERFACING WITH THE ORNL EFFORT TO ENSURE A COMPATIBLE APPROACH AND COMPLEMENTARY ACTIVITY.

TEST ELEMENT V: COMPUTER RELIABILITY

OBJECTIVES:

1. DEVELOP A METHOD FOR VERIFYING THAT DESIGN OBJECTIVES OF SAFETY SYSTEM SOFTWARE/ HARDWARE HAVE BEEN MET BY

   - DEVELOPING A METHOD FOR MODELING THE STRUCTURE OF SOFTWARE AND HARDWARE DESIGN SO THAT AUTOMATED TOOLS MAY BE APPLIED TO VERIFY THAT THE DESIGN LOGIC IS CORRECT
   - APPLYING THE MODELING AND AUTOMATED REASONING TOOLS TO EVALUATE THE RELIABILITY OF A DIGITAL SYSTEM DESIGNED FOR USE IN THE EBR-II SHUTDOWN SYSTEM
   - DEFENDING THE ANALYSIS AND ASSOCIATED SAFETY SYSTEM DESIGN THROUGH FORMAL SAFETY REVIEW

2. QUALIFY, BY ANALYSIS AND TESTING, A COMPUTER-BASED SAFETY SYSTEM FOR USE IN DYNAMIC TESTING AT EBR-II

   - ESTABLISH A COMPUTER-BASED LOW-FLOW TRIP
   - ESTABLISH A COMPUTER-BASED POWER-TO-FLOW RATIO TRIP
   - UTILIZE THE COMPUTER-BASED SAFETY SYSTEM TO SUPPORT PLANT TESTING WHERE THE SAFETY SYSTEM MUST BE RECONFIGURED
   - PROVIDE THE HARDWARE AS A TEST BED FOR BOTH CONTROL AND PROTECTION SOFTWARE DEVELOPMENT

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    - PROVIDE THE HARDWARE AS A TEST BED FOR BOTH CONTROL AND PROTECTION SOFTWARE DEVELOPMENT

TEST ELEMENT V: COMPUTER RELIABILITY (cont)

ACCOMPLISHMENTS:

A FAULT-TOLERANT COMPUTER, DESIGNED BY C. S. DRAPER LABORATORY, HAS BEEN DELIVERED TO EBR-II AND IS UNDER TEST.

METHODS OF FORMAL ANALYSIS, INCLUDING MODELING OF SOFTWARE AND HARDWARE IN A FORM SUITABLE FOR THE AUTOMATED REASONER SOFTWARE, HAVE BEEN DEVELOPED.

THE FORMAL ANALYSIS METHODS HAVE BEEN APPLIED TO THE DRAPER FAULT-TOLERANT COMPUTER AND SOFTWARE DEVELOPED BY ANL. TESTS OF THE SYSTEM ARE UNDERWAY AT EBR-II AND THE SAFETY PACKAGE IS BEING PREPARED TO TAKE THROUGH FORMAL SAFETY REVIEW.

* THIS WORK REPRESENTS EFFORTS OF A CONSORTIUM INCLUDING EBR-II AND MCS DIVISIONS OF ANL, C. S. DRAPER LABORATORY, MICHIGAN STATE AND NASA LANGLEY.

EBR-II
PLANT DIAGNOSTICS
RESULTS AND APPLICATIONS

L. R. Monson
EBR-II Division

EBR-II
PLANT DIAGNOSTICS

RESULTS

Our goal over the last several years has been to establish EBR-II as a test bed for advanced automatic control and diagnostic system technology; use applications to enhance the reliability of long-term EBR-II operation and support of advanced LMRs.

- Have computer support systems in place
- Have made good progress in automating EBR-II
- Have made good progress in diagnostic system development - supports surveillance and operation
- Have developed state-of-the-art graphics
- Have attracted the interest of many:
  EPRI, NRC, EI, Northeast Utilities, GE, Westinghouse, RI, TII, Sohar, Universities, etc., in the role of EBR-II as a test bed
- Systems being incorporated into EBR-II operation where of benefit

EBR-II

PLANT APPLICATIONS

AREAS OF DEVELOPMENT

- **DIAGNOSTIC APPLICATIONS**

  DISYS - Argon Cooling System
  CIAS - Argon Cooling System
  System State Analyzer

- **GRAPHICS DEVELOPMENT**
- **INTEGRATION WITH PLANT AUTOMATION**
- **Apply to support PLANT LIFE EXTENSION**

DIAGNOSTIC APPLICATIONS

DISYS (Diagnostic System)

- Diagnostic system developed jointly with Westinghouse Advanced Energy Systems Division
- Will be used on the Argon Cooling system
- Has been tested with real-time plant signals on the Engineering Development Work Station (SUN computers)
- Presently trying to resolve software "bugs"
- Working with Penn State

DIAGNOSTIC APPLICATIONS

SYSTEM STATE ANALYZER

- Pattern Recognition System developed by J. Mott of E I International with support from EBR-II Division.

- Based on observation that parameters (signals) defining an operating system have definite relationships to each other.

- The SSA uses the plant as a model to learn these signal relationships from, and identify operational states of the plant over time.

- The SSA surveillance function compares currently observed signal values with the "learned" signal patterns.

- Uses pattern-recognition, contrast-enhancing algorithms to establish relationships and provide estimated signal values for the observed time period, thus establishing a measure of each signal's validity, and an indication of what the current plant state is.

DIAGNOSTIC APPLICATIONS

SSA APPLICATION AND PROCESS

- **2 STEP PROCESS**
  - LEARN
  - MONITOR

- **LEARN STEP** involves acquiring plant information from DAS from a preselected group of signals, and establishing sequential state vectors. State vector variables include temperatures, pressures, flow, neutron flux, power, etc. The learned states from these vectors are transmitted to the PC, or are retained by the DAS computer.

- **MONITOR STEP** acquires current state vectors from the DAS. These are also transmitted to the PC or are processed by the DAS computer where the SSA software determines the overlap of each current state vector with learned states. Using this information, SSA estimates the new state. The estimated state is a linear combination of learned states that best match the current state vector from a pattern-recognition viewpoint. The estimated state contains estimated values for each individual signal in the selected signal group.

SSA DISPLAYS

- **2 TYPES OF GRAPHICAL DISPLAYS AVAILABLE IN SSA:**

  - **SSA SIGNATURE** is a graphical representation of the complete signal set. For each time slice it provides an indication of which observed signals are significantly higher than estimated and which are lower, and provides the average percent deviation from estimated values. This plot of normalized signal deviations, is a plant signature indicating how closely the currently observed plant state matches the learned domain.

  - **SSA Signal Plot** is a graph of a specific observed signal value compared to the estimated value of the signal. This graph is available for any signal in the selected signal group.

DIAGNOSTIC APPLICATIONS

SSA STATUS

- **CURRENT APPLICATIONS AT EBR-II**

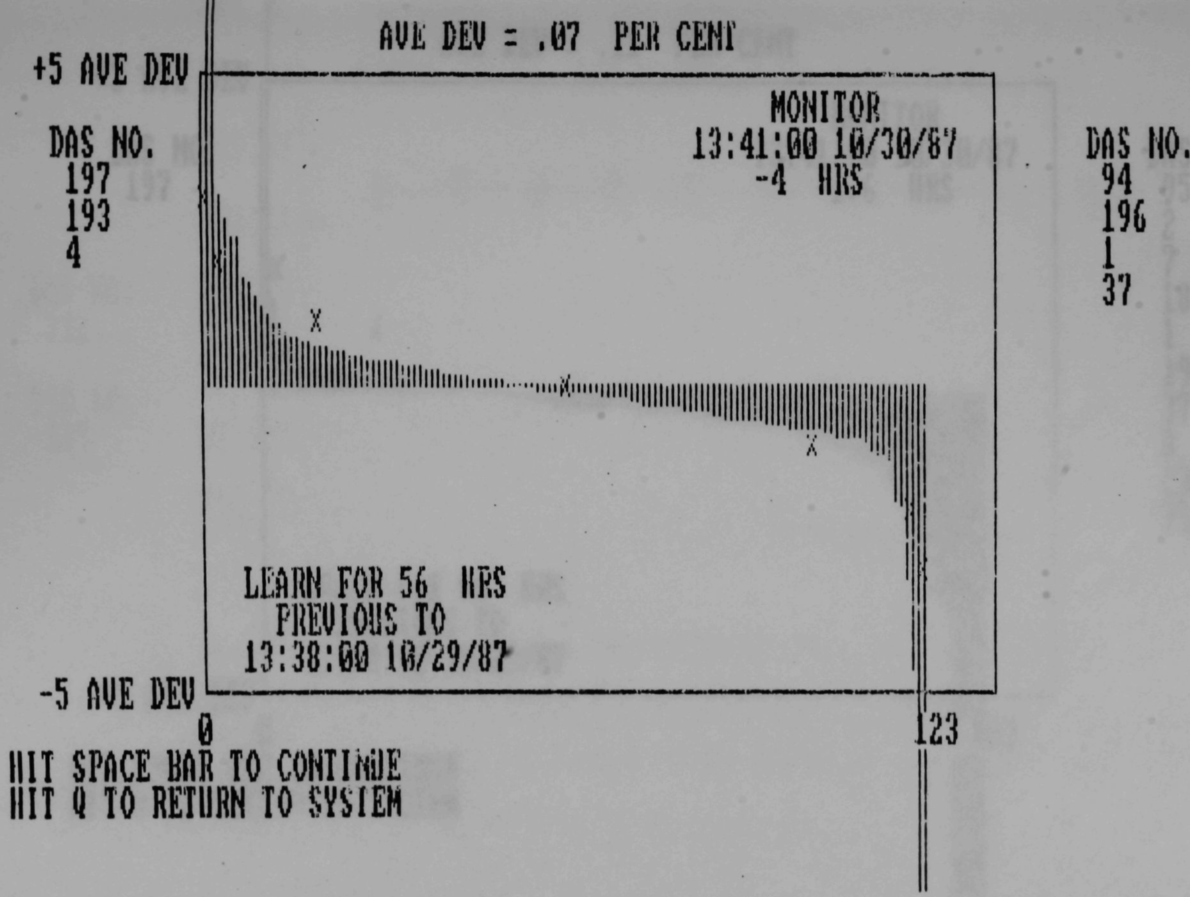
  Primary Pump Surveillance
  - Also have prototype pump diagnostic expert system running on PC

  Whole Plant Surveillance
  - Power Level Determination
  - Heat Balances (primary, secondary, steam)
  - Primary and secondary system instrumentation surveillance

  Steam System Surveillance
  - Steam Generator Performance

  Transient Test Monitoring
  - Establishing Initial Test Conditions
  - Monitoring Deviations

- **OTHER**
  - Installed in a pilot program at Northeast Utilities, interest shown by several other Utilities for instrumentation calibration reduction, non-intrusive verification of calibration, etc.


AVE DEV = .07 PER CENT
+5 AVE DEV
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94
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LEARN FOR 56 HRS
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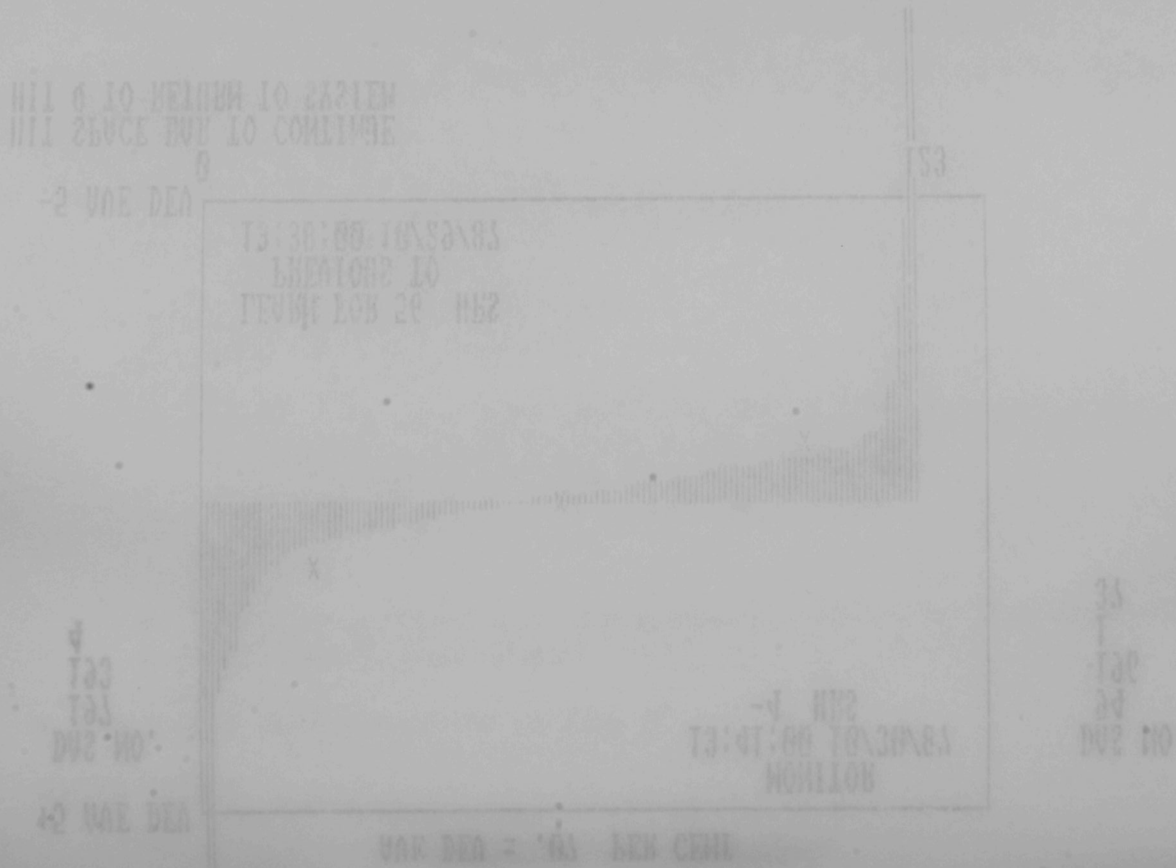
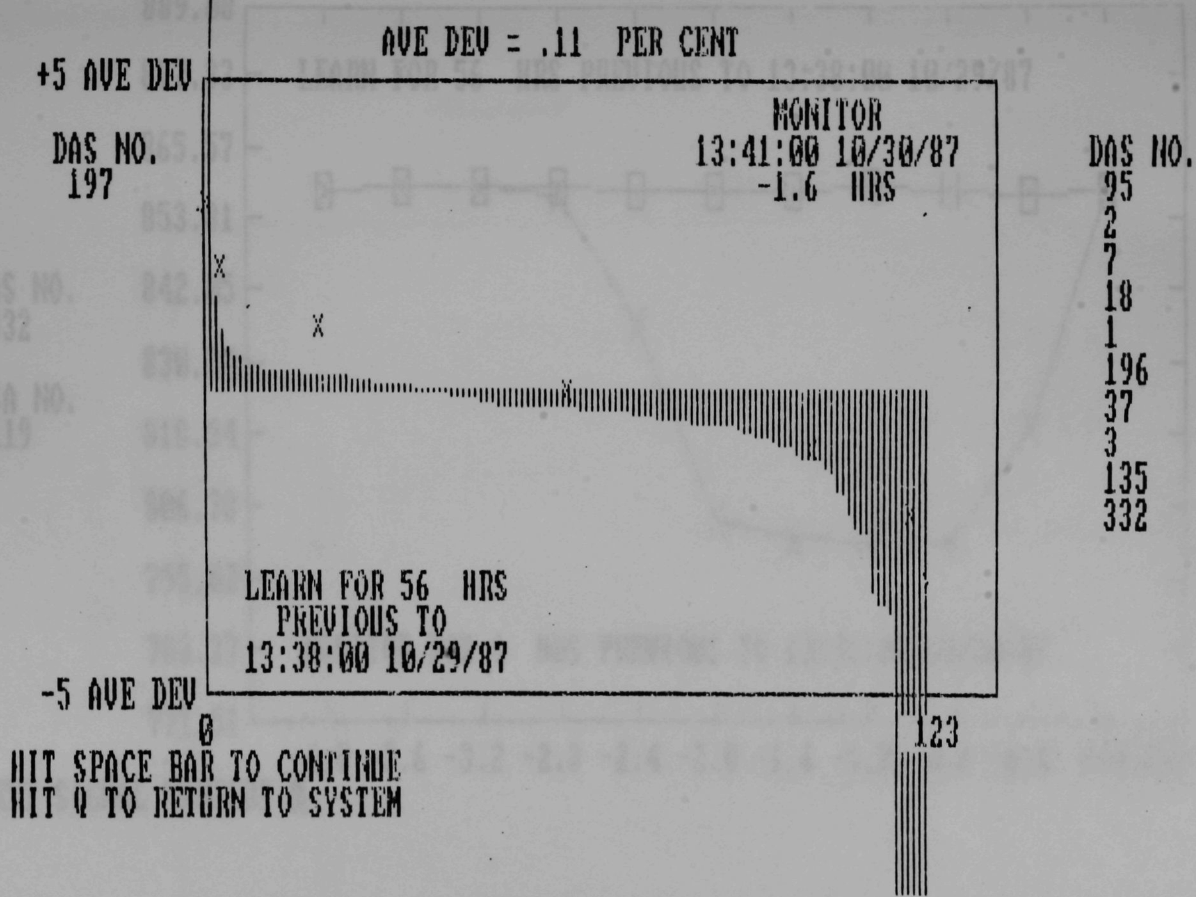
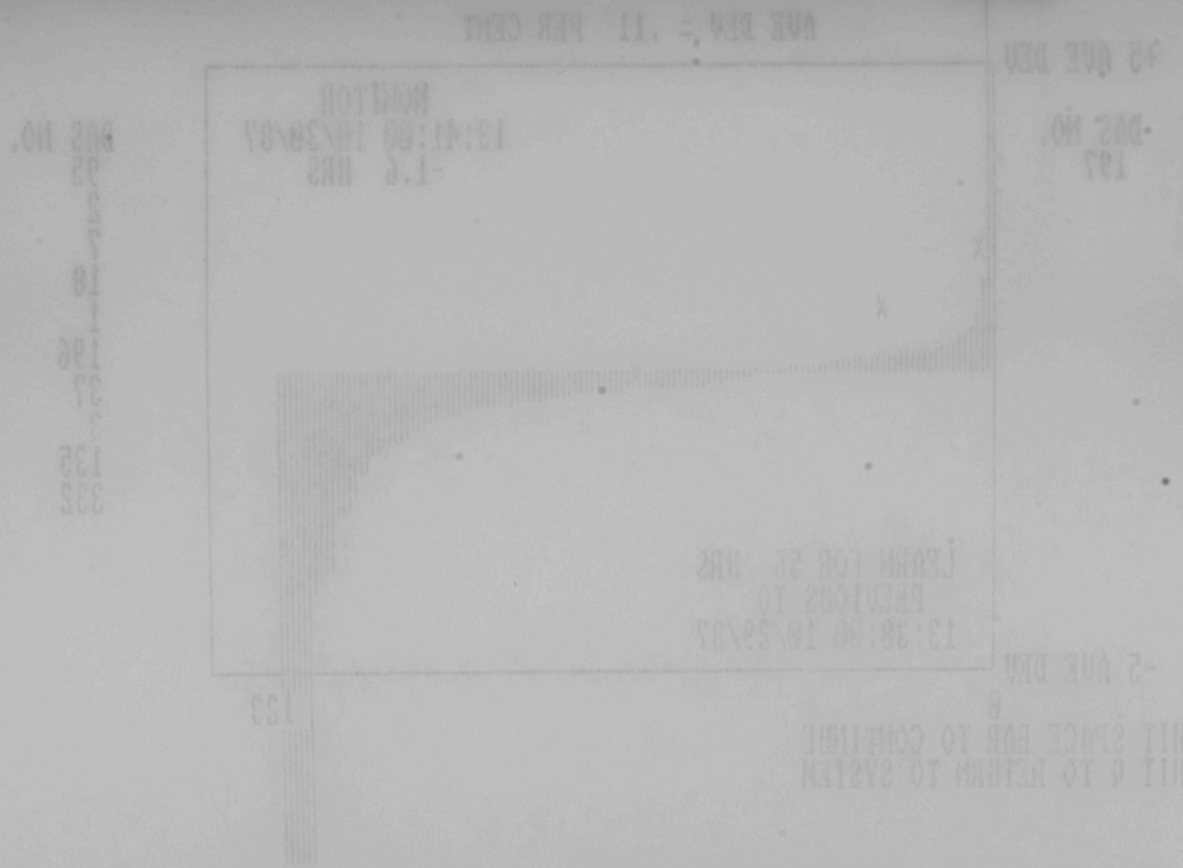
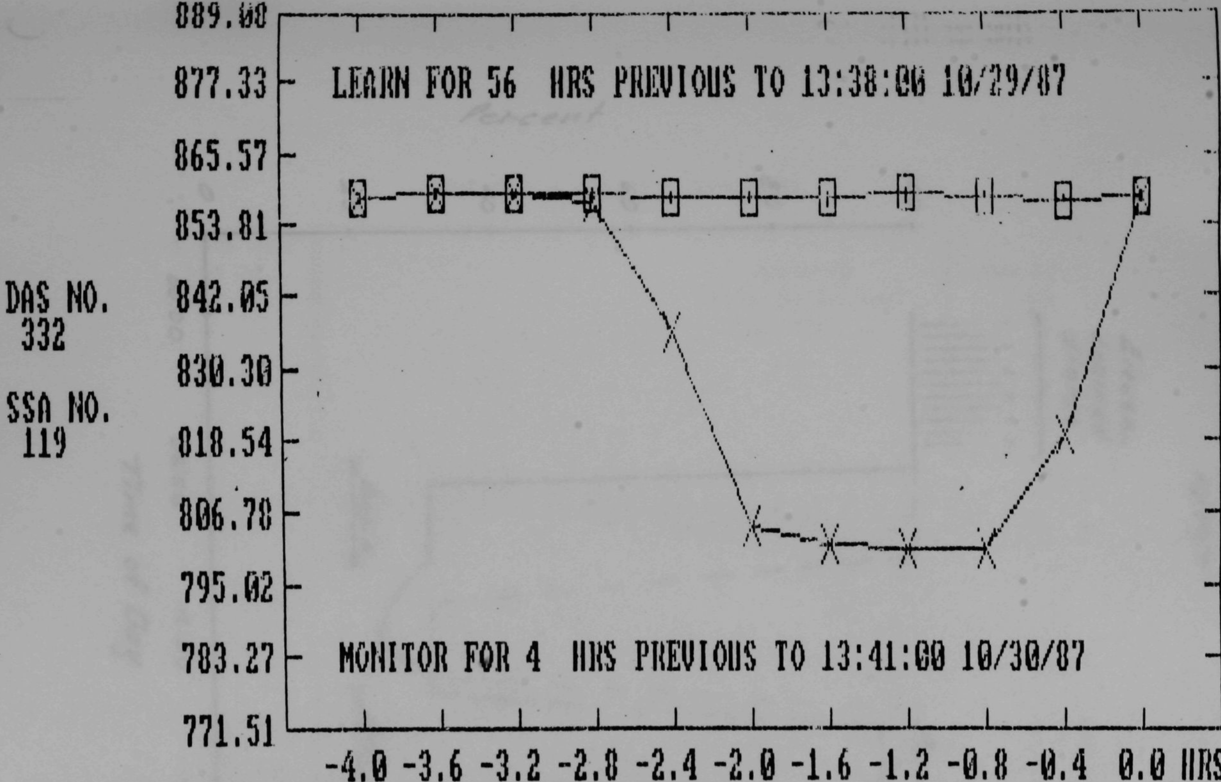
13:38:00 10/29/87
-5 AVE DEV
0
123
HIT SPACE BAR TO CONTINUE
HIT Q TO RETURN TO SYSTEM


HIT 6 TO RETURN TO SYSTEM
HIT SPACE BAR TO CONTINUE
0
-5 VOL DEV
13:36:00 10/29/87
PREVIOUS TO
LEVEL FOR 26 HRS
123
PMS NO.
192
193
4
PMS NO.
95
196
1
32
SUM 4- HRS
13:41:00 10/30/87
MONITOR
+5 VOL DEV
VOL DEV = .07 PER CENT


AVE DEV = .11 PER CENT
+5 AVE DEV
DAS NO.
197
MONITOR
13:41:00 10/30/87
-1.6 HRS
DAS NO.
95
2
7
18
1
196
37
3
135
332
LEARN FOR 56 HRS
PREVIOUS TO
13:38:00 10/29/87
-5 AVE DEV
0
123
HIT SPACE BAR TO CONTINUE
HIT Q TO RETURN TO SYSTEM



AVE DEV = .11 PER CENT
+5 AVE DEV
DAS NO.
197
MONITOR
13:41:00 10/30/87
-1.6 HRS
BUS NO.
95
18
196
37
135
332
LEARN FOR 56 HRS
PREVIOUS TO
13:38:30 10/29/87
123
-5 AVE DEV
HIT SPACE BAR TO CONTINUE
HIT 0 TO RETURN TO SYSTEM

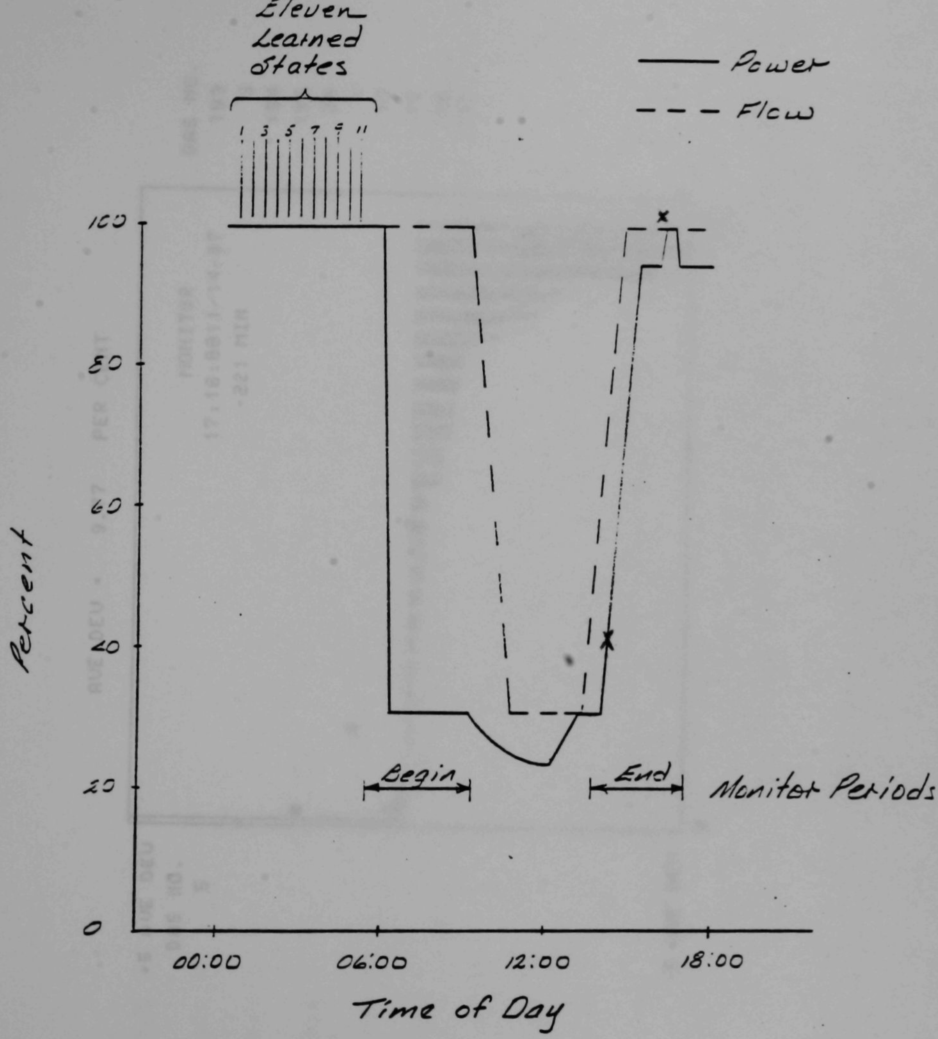


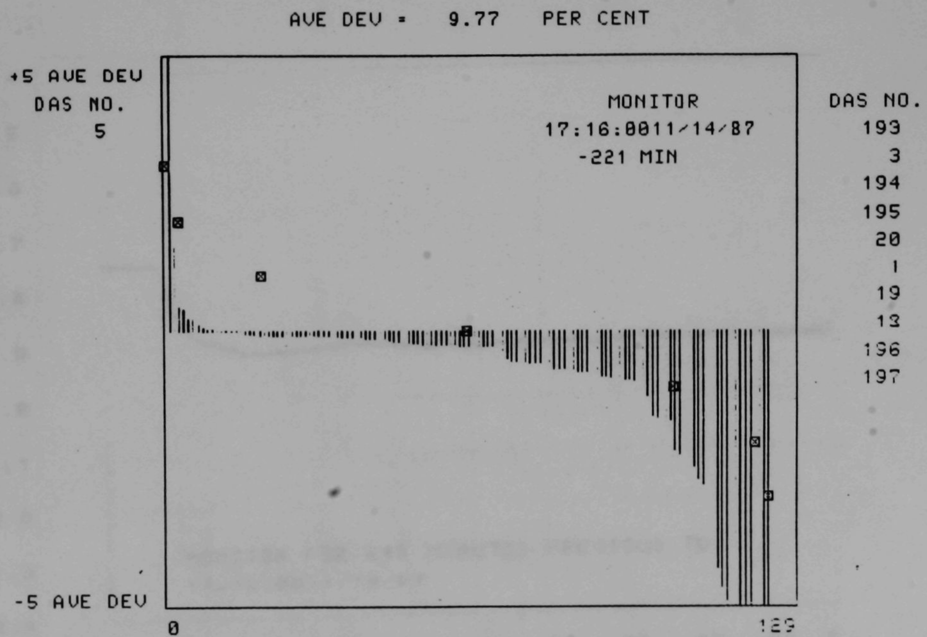
NEXT SIGNAL NUMBER?

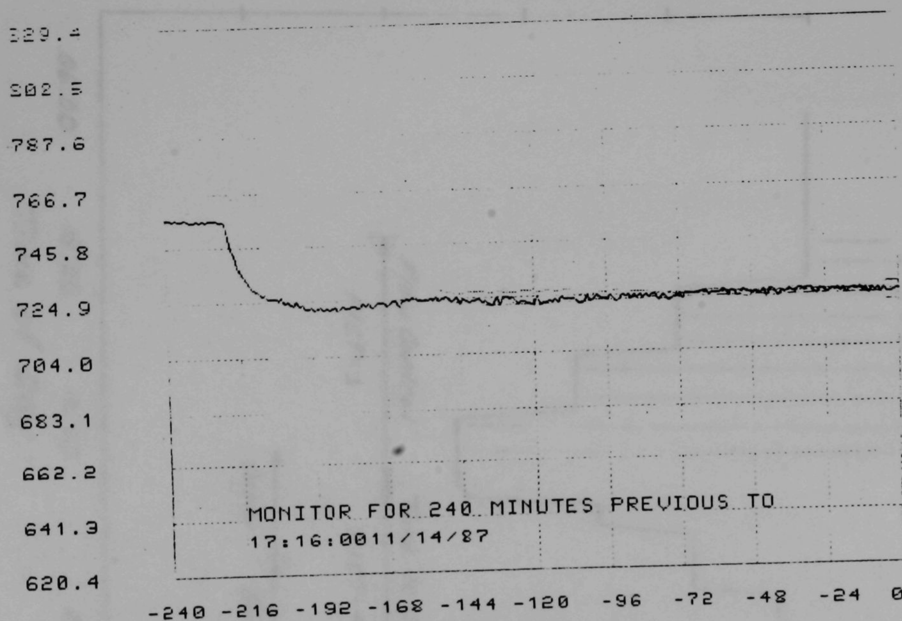
APPROXIMATE

ISOT-1

11/14/87

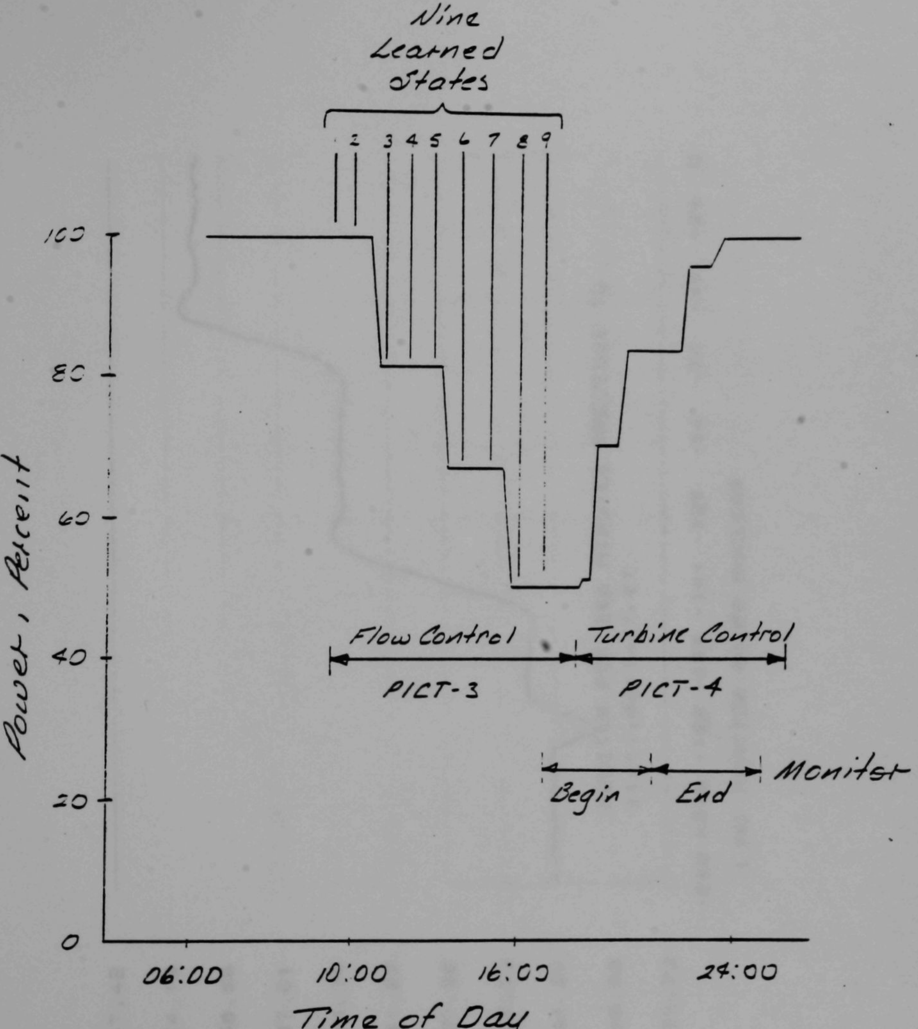


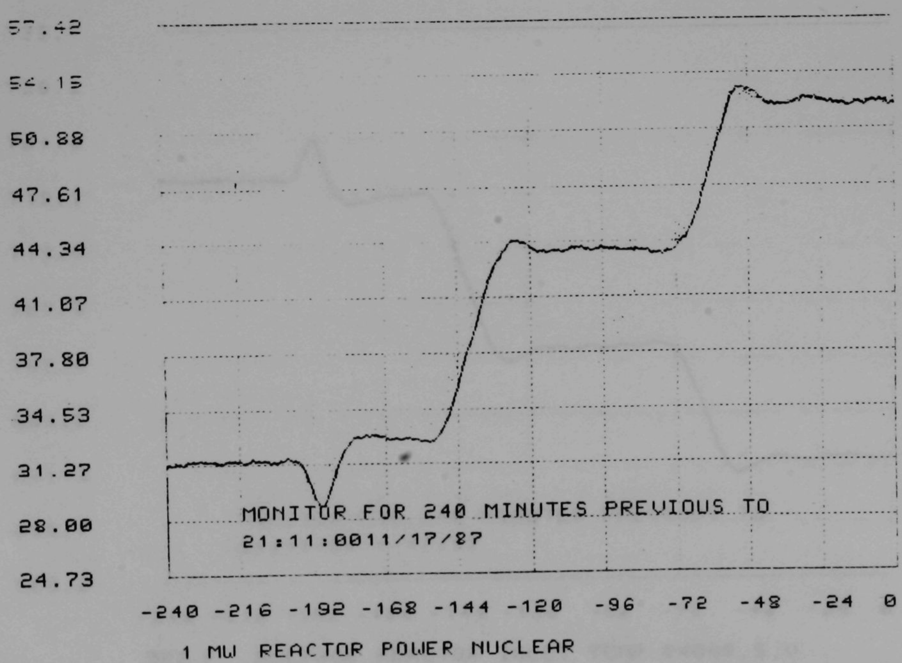

AVE DEV = 9.77 PER CENT
+5 AVE DEV
DAS NO.
5
MONITOR
17:16:0011/14/87
-221 MIN
DAS NO.
193
3
194
195
20
1
19
13
196
197
-5 AVE DEV
0
129

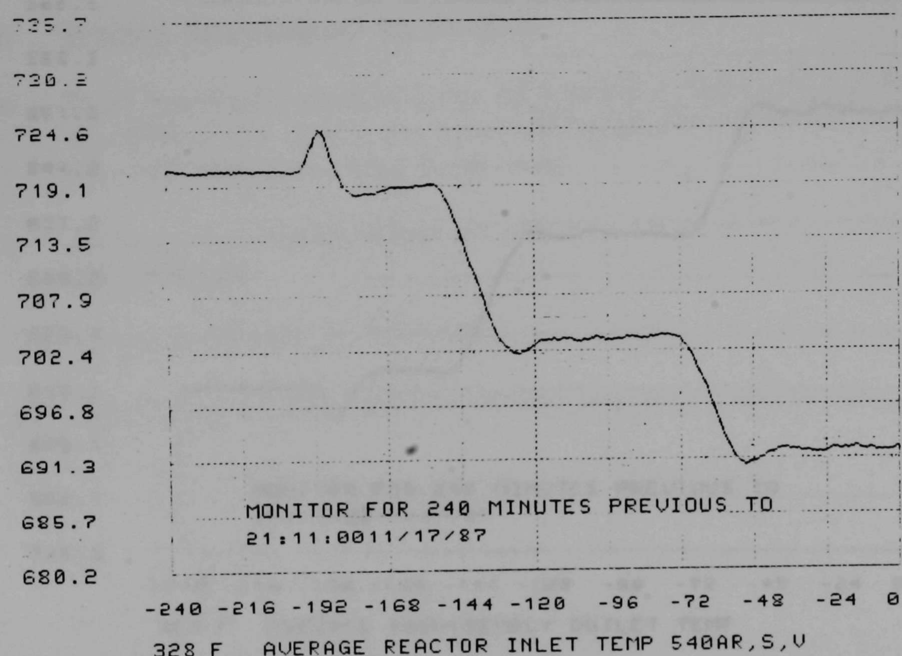


901 F PT TEMP G2 NOZZLE RAKE 2 25"

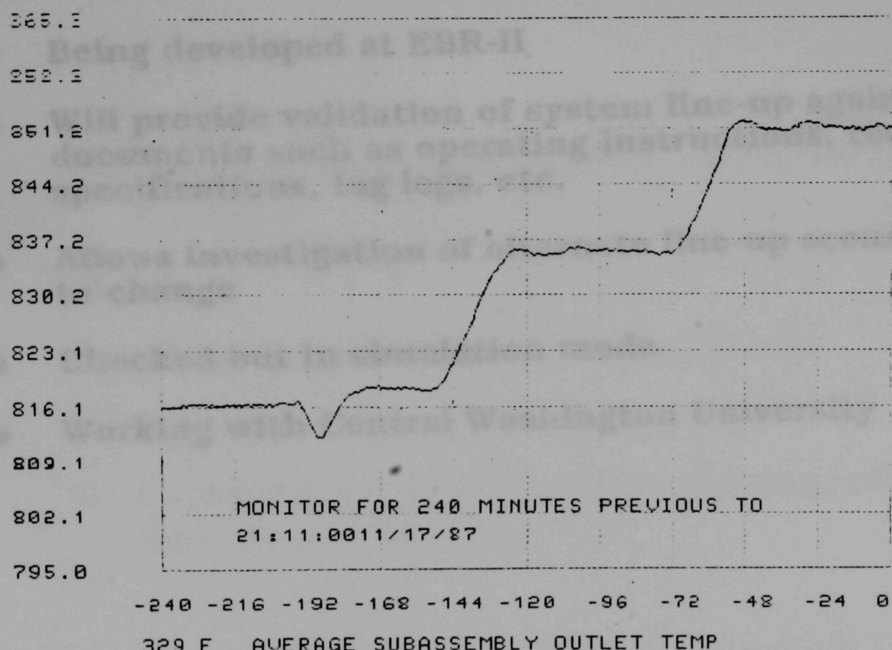
APPROXIMATE
PICT-3, 4
11/17/87




57.42
54.15
50.88
47.61
44.34
41.07
37.80
34.53
31.27
28.00
24.73
MONITOR FOR 240 MINUTES PREVIOUS TO
21:11:0011/17/87
-240 -216 -192 -168 -144 -120 -96 -72 -48 -24 0
1 MW REACTOR POWER NUCLEAR



735.7
730.2
724.6
719.1
713.5
707.9
702.4
696.8
691.3
685.7
680.2
MONITOR FOR 240 MINUTES PREVIOUS TO
21:11:0011/17/87
-240 -216 -192 -168 -144 -120 -96 -72 -48 -24 0
328 F AVERAGE REACTOR INLET TEMP 540AR,S,V


851.2
844.2
837.2
830.2
823.1
816.1
809.1
802.1
795.0
MONITOR FOR 240 MINUTES PREVIOUS TO
21:11:0011/17/87
-240 -216 -192 -168 -144 -120 -96 -72 -48 -24 0
329 F AVERAGE SUBASSEMBLY OUTLET TEMP

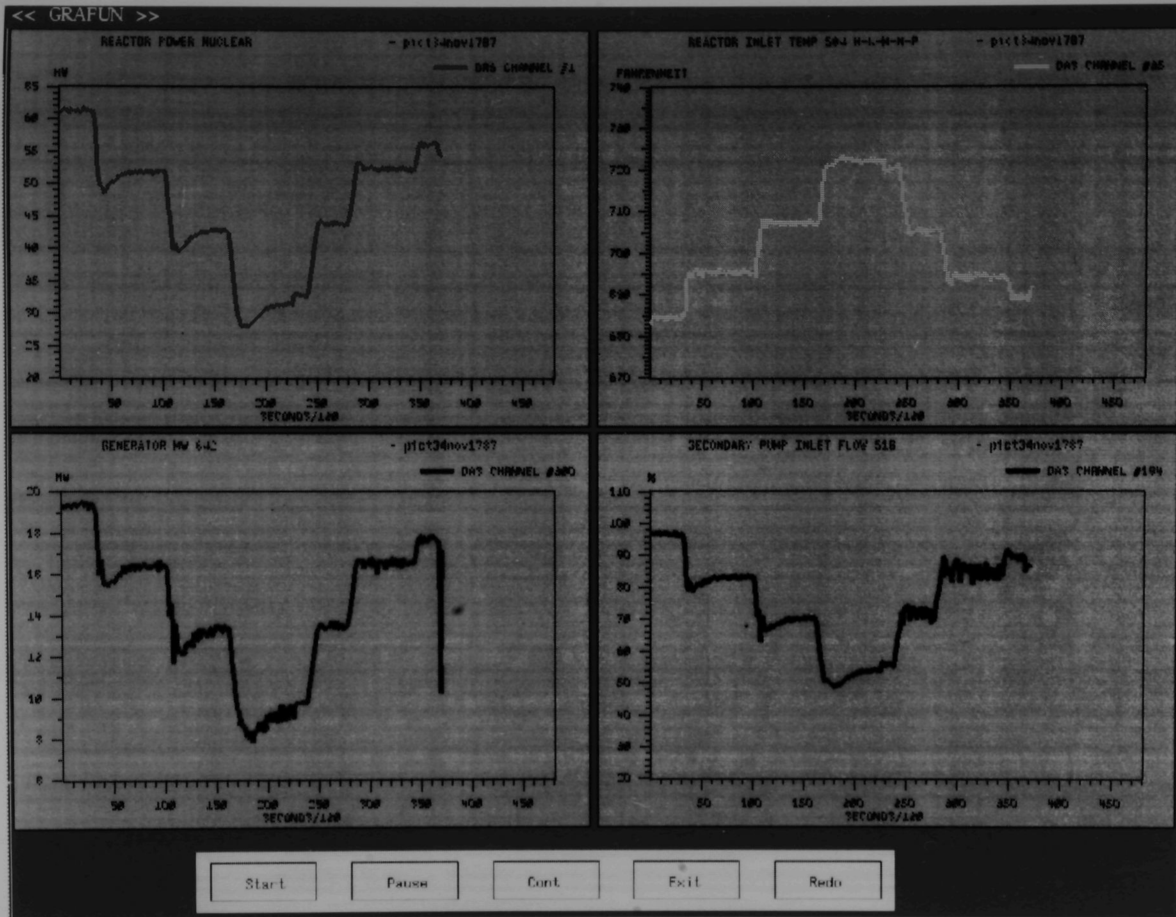
DIAGNOSTIC APPLICATIONS

CIAS (Component Impact Analysis System)

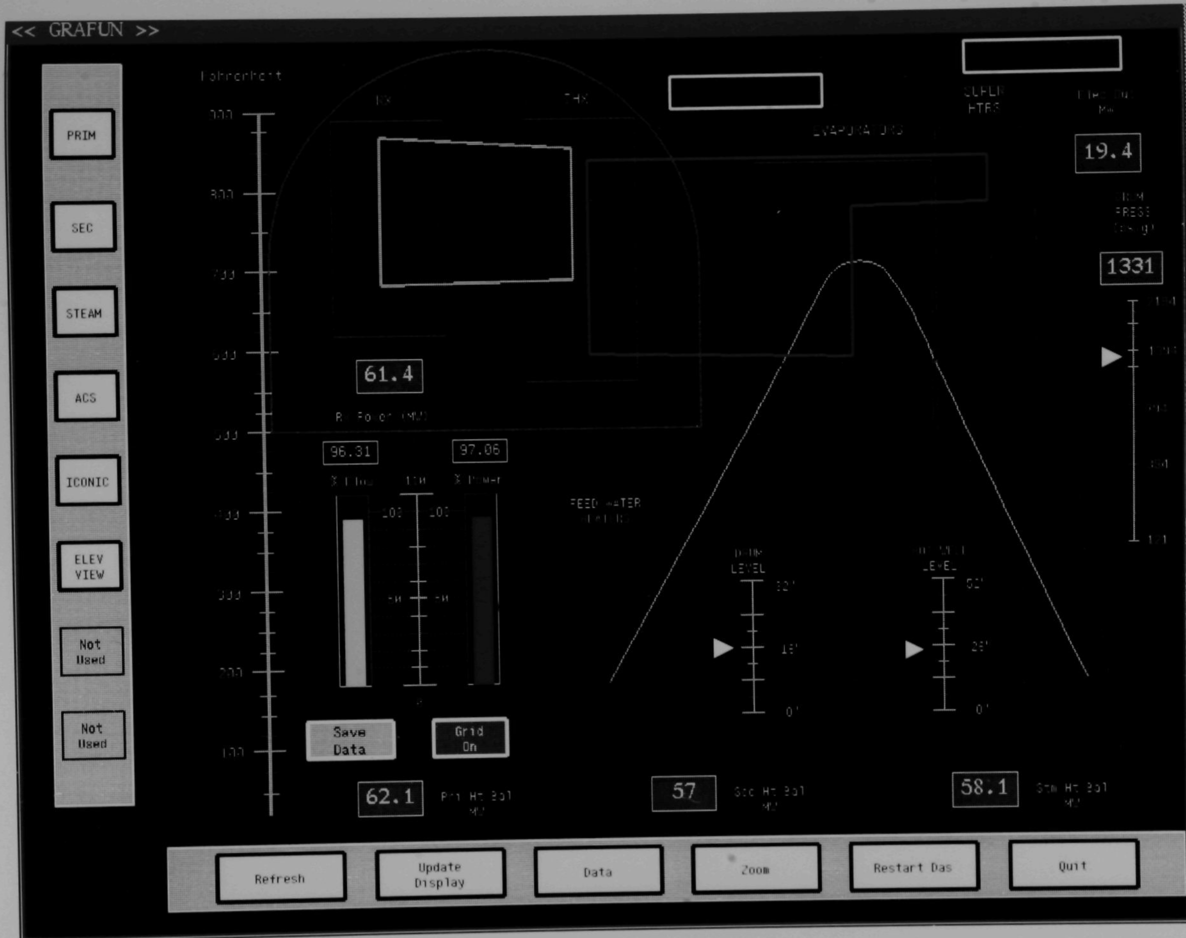
- Being developed at EBR-II
- Will provide validation of system line-up against control documents such as operating instructions, technical specifications, tag logs, etc.
- Allows investigation of alternate line-up scenarios prior to change
- Checked out in simulation mode
- Working with Central Washington University

GRAPHICS APPLICATIONS

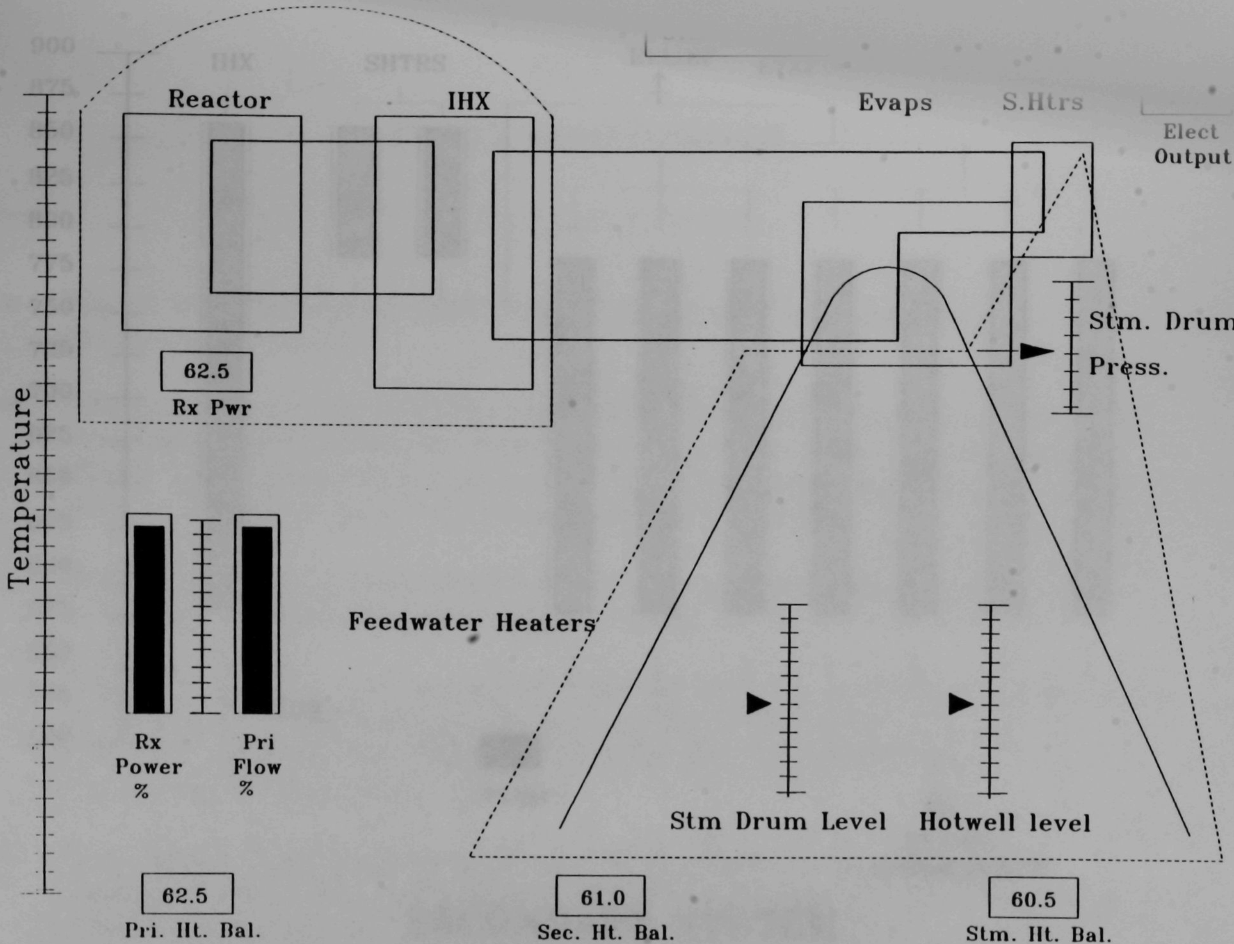
- Depicts thermodynamic cycle of the EBR-II Facility
- Utilizes real-time plant signals
- Concept of T-S diagram pioneered by Leo Beltracchi (NRC)
- Being integrated with Diagnostic tools



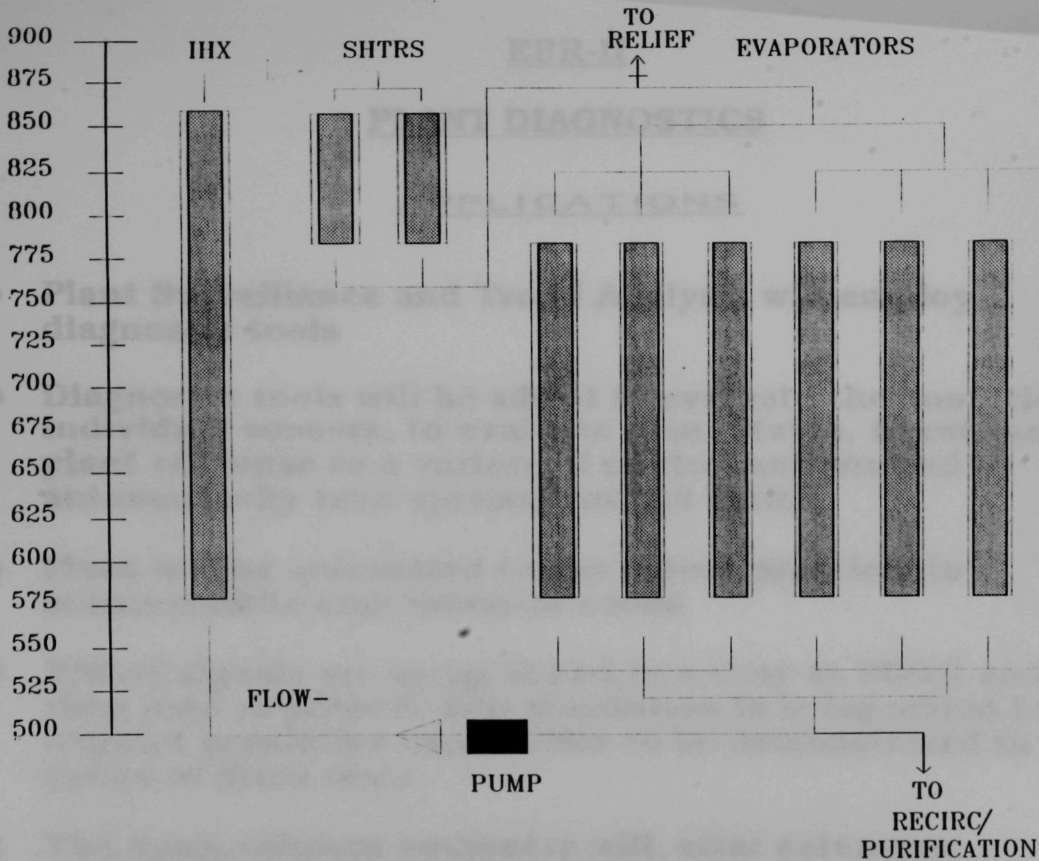
<< GRAFUN >>
REACTOR POWER NUCLEAR
DAS CHANNEL #1
MW
SECONDS/10
REACTOR INLET TEMP
FAHRENHEIT
SECONDS/10
GENERATOR MW
- pict34nov1787
MW
SECONDS/10
SECONDARY PUMP INLET FLOW 516
- pict34nov1787
%
SECONDS/10
Start
Pause
Cont
Exit
Redo



<< GRAFUN >>
PRIM
SEC
STEAM
ACS
ICONIC
ELEV VIEW
Not Used
Not Used
19.4
1331
61.4
96.31
97.06
Save Data
Grid On
62.1
57
58.1
Refresh
Update Display
Data
Zoom
Restart Das
Quit



MAIN DISPLAY



SECONDARY SYSTEM

EBR-II

PLANT DIAGNOSTICS

APPLICATIONS

- **Plant Surveillance and Trend Analysis will employ diagnostic tools**
- **Diagnostic tools will be added to evaluate the condition of individual sensors, to evaluate plant status, to estimate plant response to a variety of control actions and to automatically take optimal control action**
- **Plant will be automated to the extent practical to accommodate experimenter needs**
- **EBR-II signals are being linked to a Cray at EG&G and real time (and possible faster) simulation is being added to support predictive capabilities to be demonstrated in a series of plant tests**
- **The Fault-tolerant computer will, after extensive qualification, be incorporated as a re-configurable reactor shutdown system to accommodate a variety of control approaches and tests**

EBR-II

PLANT DIAGNOSTICS

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PLANT SAFETY TESTS AND IMPLICATIONS

W. K. Lehto
EBR-II Division

PLANT TESTS

Test Program Overview (EBR-II Impacts)

The EBR-II Test Program has been structured to demonstrate the inherent safety features of metal fueled LMR's and to redefine the EBR-II safety position. The program addresses bounding events that provide pathways into an HCDA.

- Events leading to a HCDA are:
  - Loss of flow without scram
  - Loss of heat sink without scram
  - Transient Overpower
    - Rod insertion/run-out with positive reactivity insertion
    - Pump overspeed events
    - Balance of plant cooldown

PLANT TESTS
(cont'd)

- LOFWS and LOHSWS were addressed in the February and April 1986 tests. These tests conclusively demonstrated passive shutdown of EBR-II for bounding loss of cooling events. Subsequent analysis, based on a damage function correlation developed from the XY-22 eutectic penetration experiment, showed that pump coastdown times of the order of 50 seconds would not result in unacceptable driver fuel damage. Recent work indicates pump coastdown times much shorter than 50 sec. will not result in fuel damage.

- Rod insertion events have been addressed in EBR-II in the context of rate and total worth of insertion and analysis shows that fuel melting due to reactivity induced overpower is incoherent in space and time and thus does not provide a pathway into an HCDA. This point was discussed in depth at the National Research Council Review of EBR-II in January, 1988.

PLANT TESTS
(cont'd)

<u>Pump Overspeed/Overcooling Events</u>

- The results of the Inherent Operability Test-1 (IOT-1) conducted in November 1987 provide a basis to address pump overspeed/sudden core cooling events in EBR-II.

- This test was done from 20 Mw @ 32% flow (P/F=1) by increasing reactor primary system flow to 100% in 20 seconds. The power followed and increased to near 100% due to the positive reactivity feedbacks induced by the flow increase. There was no control rod action during the test.

PLANT TESTS
(cont'd)

Test Objectives — IOT-1

- Obtain reactor power response to a rapid increase in primary flow with no control rod motion and demonstrate safe response to pump run-up events.

- Provide data for code verification for subsequent analysis of pump run-up and cold sodium slug events

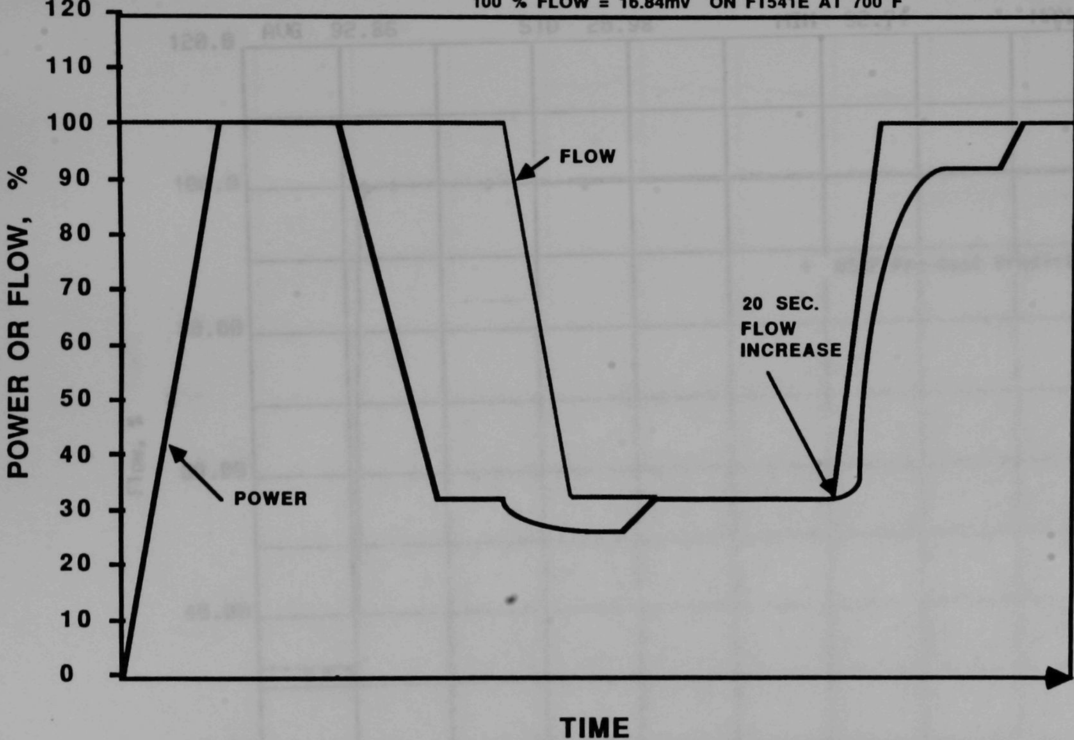
- Obtain reactor power response to changes in tank stratification

- Measure the reactivity addition required to go from equilibrium power (following pump run-up) to 100% power, This reactivity is a measure of the fuel coefficient of reactivity. Measurement is subject to interference from other small feedback effects such as tank stratification, etc.

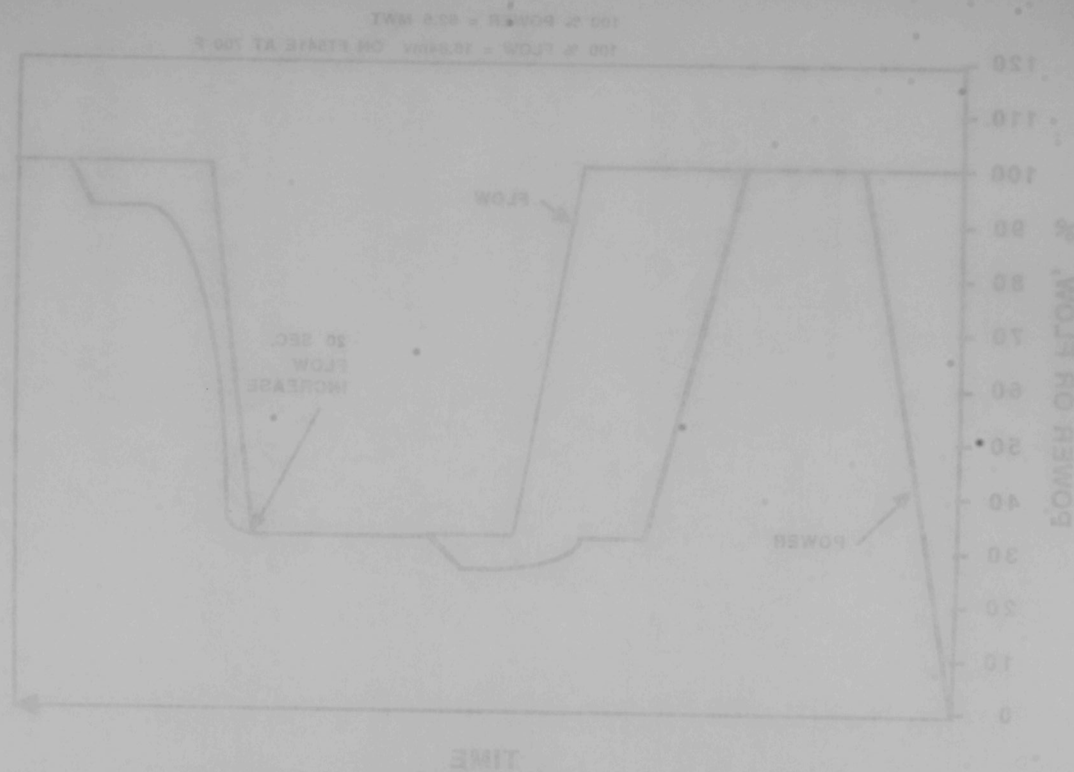
100 % POWER = 62.5 MWT

100 % POWER = 62.5 MWT

100 % FLOW = 16.84mv ON FT541E AT 700 F



IOT-1 TEST



100 % POWER = 62.5 MWT
POWER OR FLOW, %
0
10
20
30
40
50
60
70
80
90
100
110
120
FLOW
POWER
20 SEC.
FLOW
INCREASE
TIME

IOT-1 TEST

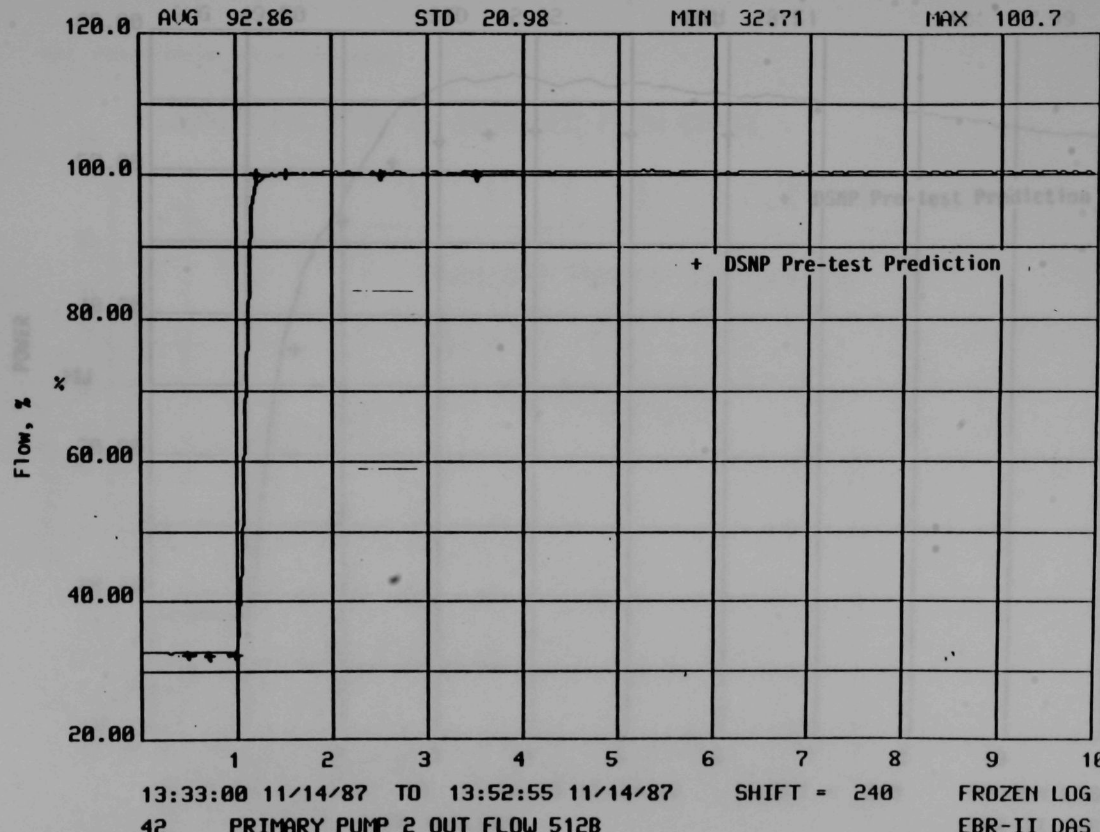


Fig. I IOT-1 Test Results
20 Minute Frozen Log (2 x Time Scale)

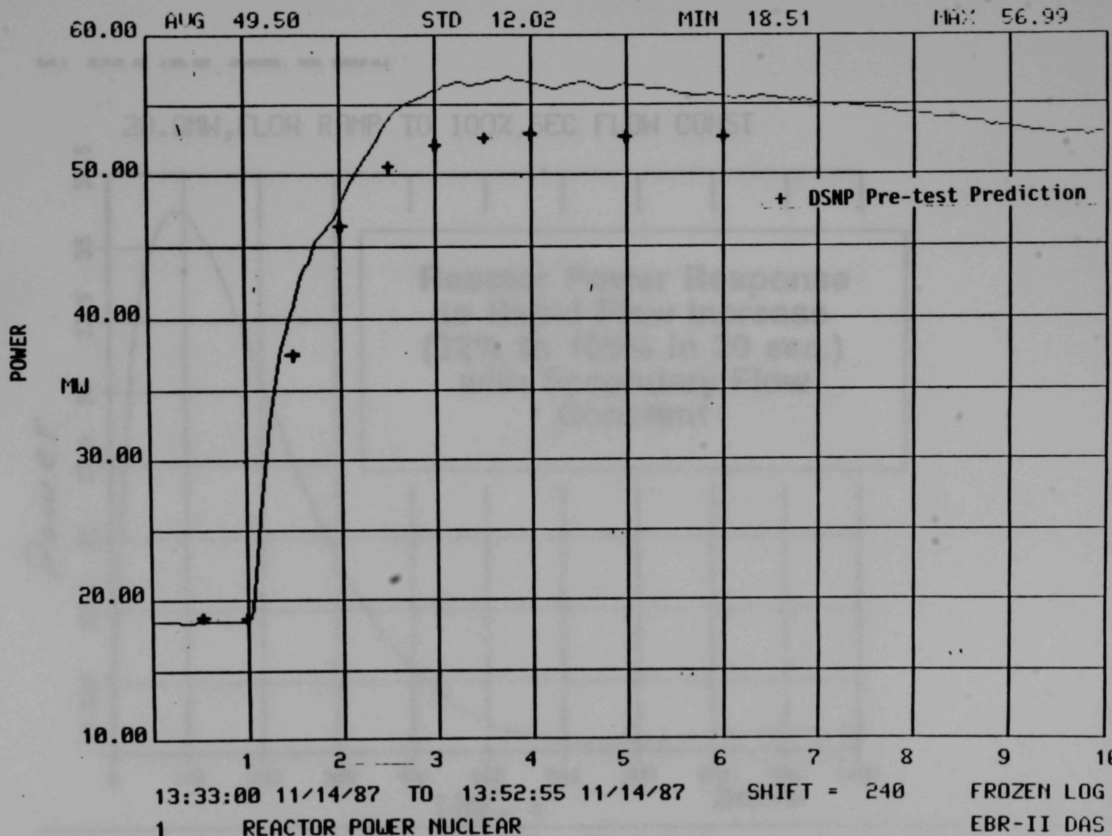
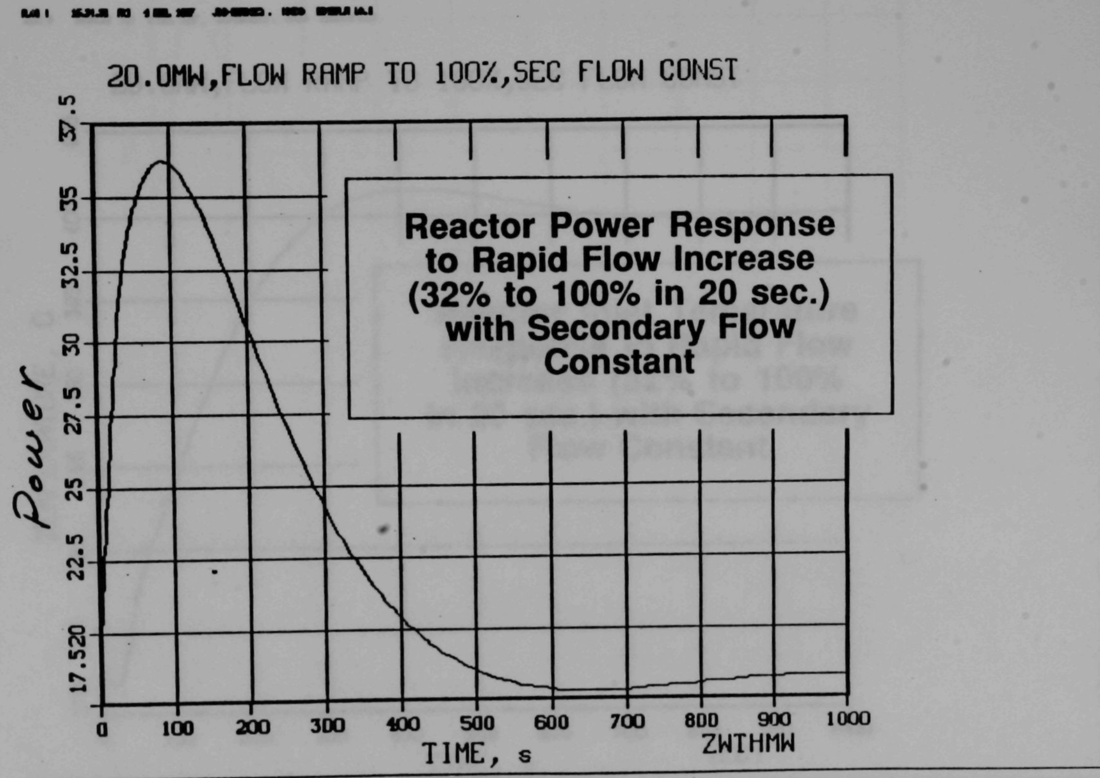
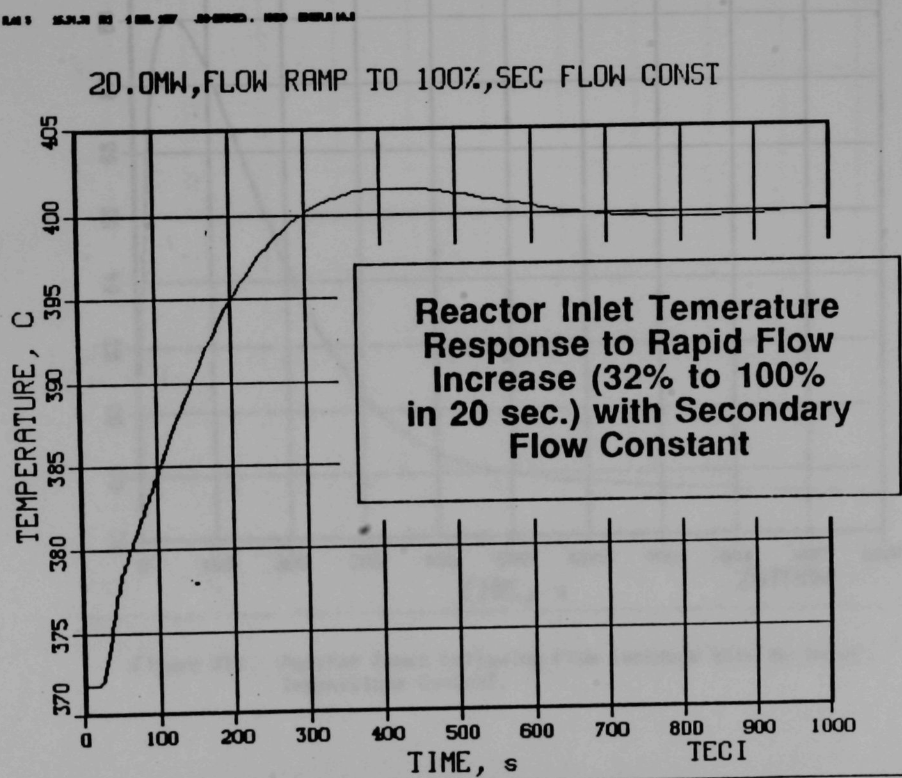


Fig. II IOT-1 Test Results

20 Minute Frozen Log (2 x Time Scale)



20.0MW,FLOW RAMP TO 100%,SEC FLOW CONST
Reactor Power Response to Rapid Flow Increase (32% to 100% in 20 sec.) with Secondary Flow Constant
Power
37.5
35
32.5
30
27.5
25
22.5
17.520
0
100
200
300
400
500
600
700
800
900
1000
TIME, s
ZWTHMW


20.0MW,FLOW RAMP TO 100%,SEC FLOW CONST
Reactor Inlet Temerature
Response to Rapid Flow
Increase (32% to 100%
in 20 sec.) with Secondary
Flow Constant
TEMPERATURE, C
370
375
380
385
390
395
400
405
0
100
200
300
400
500
600
700
800
900
1000
TIME, s
TECI

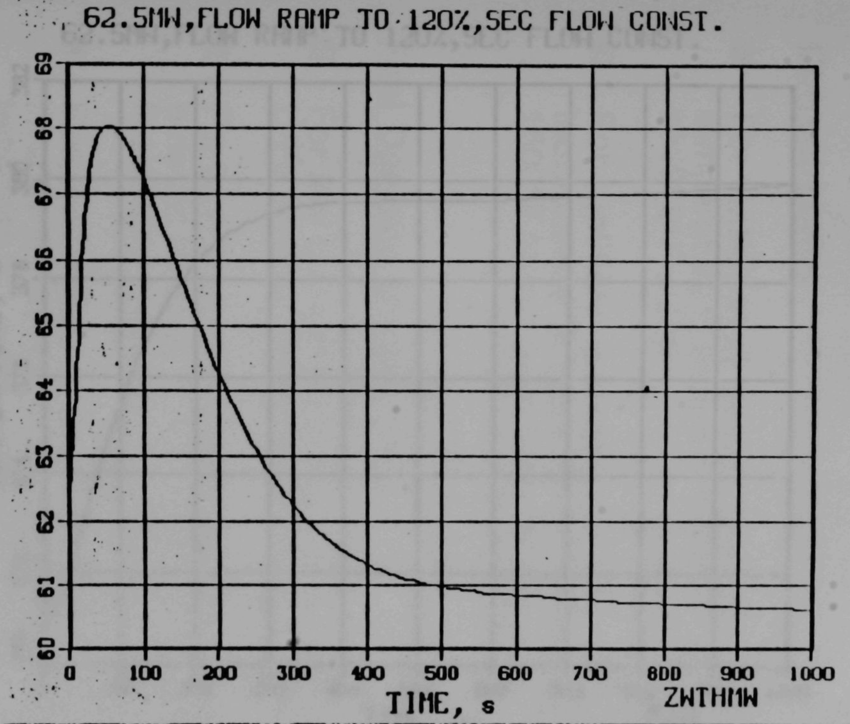


Figure XVI. Reactor Power Following Flow Increase With No Inlet Temperature Control.

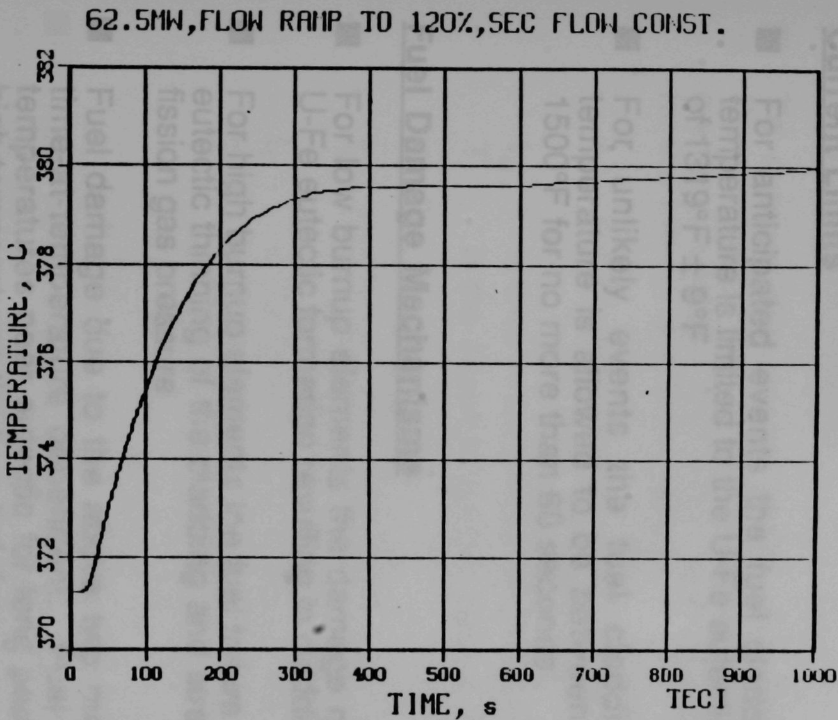


Figure XV. Reactor Inlet Temperature Response to Flow Increase with No Secondary System Flow Control.

DEVELOPMENT OF SAFETY LIMITS FOR ADVANCED METAL FUEL IN EBR-II

Current Limits

- For anticipated events the fuel cladding interface temperature is limited to the U-Fe eutectic temperature of 1319°F ± 9°F
- For unlikely events the fuel cladding interface temperature is allowed to be between 1319°F and 1500°F for no more than 60 seconds

Fuel Damage Mechanisms

- For low burnup elements the damage mechanism is U-Fe eutectic formation resulting in cladding wastage
- For high burnup elements the fuel failure is caused by eutectic thinning of the cladding and stress rupture to fission gas pressure
- Fuel damage due to the above two mechanisms is time-at-temperature dependent. Fuel can sustain temperatures near eutectic for long periods while at high temperatures the time to failure is much shorter

DEVELOPMENT OF SAFETY LIMITS FOR ADVANCED METAL FUEL IN EBR-II
(cont.)

Fuel Failure Correlations

- To support the recent SHRT and Inherent Safety Demonstration Tests in EBR-II, failure correlations for cladding wastage and stress rupture were developed for the MK-II, U-5Fs fuel design

  - $t_e = 5.5 \times 10^{-15} e^{44574/T}$

    t_e is time in seconds to penetrate cladding
    T is the absolute temperature — °K

  - $t_r = 509 \left[\left(-14.1 + 12.6\,(\%BU)\right) T/811\right]^{-6} 10^{13282/T}$

    t_r is the time to rupture the cladding
    %BU is the fuel burnup in at.%
    T is the absolute temperature — °K

- These correlations were verified prior to the SHRT tests with an in-reactor experiment in EBR-II called XY-22. An orificed subassembly was placed in core and brought to power to create temperatures higher than eutectic in the fuel. The highest fuel-cladding interface temperature attained was 1472°F and the test ran for 42 minutes at these temperatures prior to failure

DEVELOPMENT OF SAFETY LIMITS FOR ADVANCED METAL FUEL IN EBR-II

(cont.)

Damage Function

■ To evaluate fuel conditions during the SHRT tests a damage function approach was used

$$d = \int \frac{dt}{t^*}$$

d is the fractional damage
t* is the smaller of to t_e or t_r

■ For the SHRT test series the acceptable damage was set at 25%. The actual damage in the hottest fuel pin in the core was calculated to be much less than 1% for both the SHRT 45 and the Inherent Safety Demonstration Test (April 1986)

DEVELOPMENT OF SAFETY LIMITS FOR ADVANCED METAL FUEL IN EBR-II

(cont.)

Advanced Fuel Limits

- The approach would be to develop time to failure correlations as was done for the EBR-II MK-II fuel

- The steady state and transient safety limits would be based on an acceptable damage to the fuel. This approach would show that very severe, short duration accidents to near coolant boiling conditions would not result in life-limiting fuel damage

- For the MK-IV fuel several types of data are needed in order to develop time to failure correlations. These are:

  - Furnace tests to accurately measure the eutectic temperature and the eutectic penetration rate as a function of temperature

  - In-furnace rupture tests on MK-IV fuel pins to establish time-to-rupture data as a function of burnup and temperature

  - An in-reactor test in EBR-II similar to XY-22 to provide confirmatory data on time-to-rupture and failure mode. This may require more than one test, e.g., a test using low burnup elements to confirm the cladding wasteage correlation and a test on high burnup elements to confirm stress rupture models. Temperature effect data are automatically obtained in each test because of the temperature distribution within the test assembly

DEVELOPMENT OF SAFETY LIMITS FOR ADVANCED METAL FUEL IN EBR-II
(cont.)

Advanced Fuel Limits

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EBR-II SEVERE ACCIDENT ANALYSIS

- Conclusion from EBR-II Testing Program is that there is no credible LOF or LOHS without scram that leads to an accident that results in fuel failure, let alone an HCDA. In addition an unprotected TOP has been shown by analysis to lead to incoherent melting of fuel, therefore it also does not lead to HCDA

- The above arguments provided the bases for our discussions during the National Research Council Review in January, 1988.

PLANT INHERENT CONTROL TESTS

IMPLICATIONS FOR FUTURE PLANT DESIGN

ARGONNE NATIONAL LABORATORY
WEST
UNIVERSITY OF CHICAGO

H. P. Planchon
EBR-II Division

Objectives:

Develop and test approaches to design and control of LMR's that will:

1. Provide inherently safe response of the LMR to all types of operational accidents

2. Provide high operating reliability

3. Simplify designs; particularly of safety systems

I will return & discuss these objectives in more detail later for now you can see they are extension of the objective & successes we had in the Inherent Safety Demonstration Test Program

EBR-II payoff

1. Safety is significantly enhanced by test programs 2 points here
   - Real safety improved — upgraded speed controls for SASS ~~[illegible]~~ separated, virtually eliminated single failures trip both pumps
   - Licensibility

2. Design simplification supported by test results and computer codes validated with test data

3. Operating reliability and flexibility

Quite aside from the ~~design~~ importance to future LMR designs the Tests are very important for EBR II

— There is a direct payoff

TESTING PROGRAM EVOLUTION

- The EBR-II" Inherent Safety Demonstration Tests " demonstrated the folowing:

  —Passive shutdown for loss of flow without scram
  —Passive shutdown for loss of heatsink without scram
  —Passive heat removal via natural convection

- But there are outstanding safety and operational issues

  —Can transient overpower be passively accommodated ?
  —Can control systems be designed that will not over-ride the inherent feedbacks and prevent a passive shutdown ?
  —Can one utilize passive feedback and control features and simplify LMR designs ? ~~design utilize inherent safety to simplify~~
  ~~The GE&AI design approach significantly the followed this.~~

- Recent PICT results indicate that these issues may be favorably resolved with passive reactor control schemes

We expect our tests will validate the GE&AI approach of ~~safety~~ simplify safety systems. Perhaps results will suggest further simplification,

PLANT INHERENT CONTROL TESTS

- Tests investigate minimum use of control rods for reactor power control and fuel burnup compensation
- Five tests involving reactor power changes
  —Power range 40% to 100%
  —No control rods used
  —Thermodynamic state controlled with pumps and turbine throttle
- Plant generated electrical power and exported it to the grid during all tests
- Tests designed conservatively. Reactor temperatures were kept below normal power temperatures at all times
- Extensive safety analysis. Examined consequences of equipment failures as well as controlled failures during testing

THE EBR-II (LMR) CONTROL PROBLEM

62
.09
$\boxed{2.98}$

The main 5 pieces of equipment that control EBR-II power generation process are:

- C1 — Control rods
- C2 — Main coolant pumps
- C3 — Secondary Sodium Pump
- C4 — Turbine Throttle
- C5 —Steam pressure regulating valve

Normal EBR-II Control:

- Rods C1 adjusted to give desired power
- MCP C2 controlled to 100% flow
- Secondary Pump C3 controlled to remove heat and keep reactor inlet constant (700° F)
- Throttle C4 controlled steam flow to keep steam pressure constant (1250 psi)

Control in tests

C1 rods deenergized

Reactor power controlled by inherent reactivity feedbacks

Feedbacks tend to keep effective (sodium/steel) temperature constant

So power level controlled by heat removal
—Pumps and turbine throttle

CONTROL OF REACTOR POWER WITH PRIMARY FLOW AND REACTOR INLET TEMPERATURE

REACTIVITY FEEDBACK - Lumped Parameters

$$\delta\rho = A\delta(P) + B\delta(P/F) + C\delta T_I + \rho_{RODS}$$

FOR CHANGES IN FLOW

$$0 = \delta\rho = A\delta(P) + B\delta(P/F)$$

OR

$$P = F \frac{1 + A/B}{1 + (A/B)F}$$

FOR CHANGES IN INLET TEMPERATURE

$$0 = \delta\rho = (A+B)\ \delta\rho + C\delta T_I$$

OR

$$\delta P = \frac{C}{A+B}\ \delta T_I$$

APPROXIMATE VALUES

$$\frac{A}{B} \simeq 0.15 \quad \frac{C}{A+B} \simeq 0.15 \ \frac{\%\ \text{POWER}}{^{\circ}\text{F}}$$

CONTROL OF REACTOR POWER WITH PRIMARY FLOW AND REACTOR INLET TEMPERATURE

REACTIVITY FEEDBACK - Lumped Parameters

$$\delta\rho = A\delta(P) + B\delta(P/F) + C\delta T_I + \rho_{RODS}$$

FOR CHANGES IN FLOW

$$0 = \delta\rho = A\delta(P) + B\delta(P/F)$$

OR

$$P = F \frac{1 + A/B}{1 + (A/B)F}$$

FOR CHANGES IN INLET TEMPERATURE

$$0 = \delta\rho = (A+B)\,\delta\rho + C\delta T_I$$

OR

$$\delta P = \frac{C}{A+B}\,\delta T_I$$

APPROXIMATE VALUES

$$\frac{A}{B} \approx 0.15 \qquad \frac{C}{A+B} \approx 0.15 \ \frac{\%\ POWER}{°F}$$

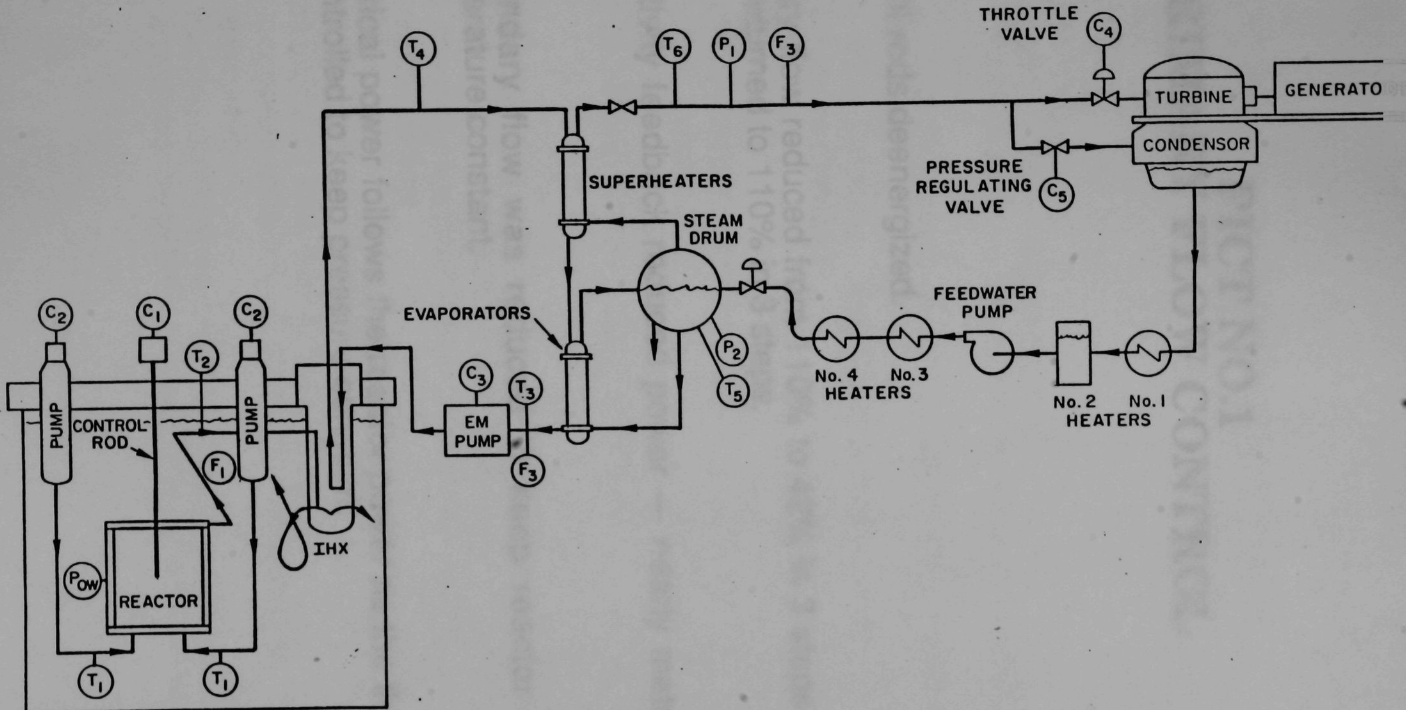
NOTES 1

- This lumped parameter reactivity equation is useful to estimate trends but it isn't very accurate because the PRD is not linear and because the values of A, B and C change with core loading.

- The values are approximately consistent with
  PRD = A+ B = 27¢
  Inlet temperature coefficient C = 0.4¢/ °F
  A = 3.5¢
  B = 23.5

- If A/B = O then power would follow primary flow and keep P/F = 1.0 Actually the P/F ratio increases to about 109% when going from 100% power to 40% power. You will see that in test 1

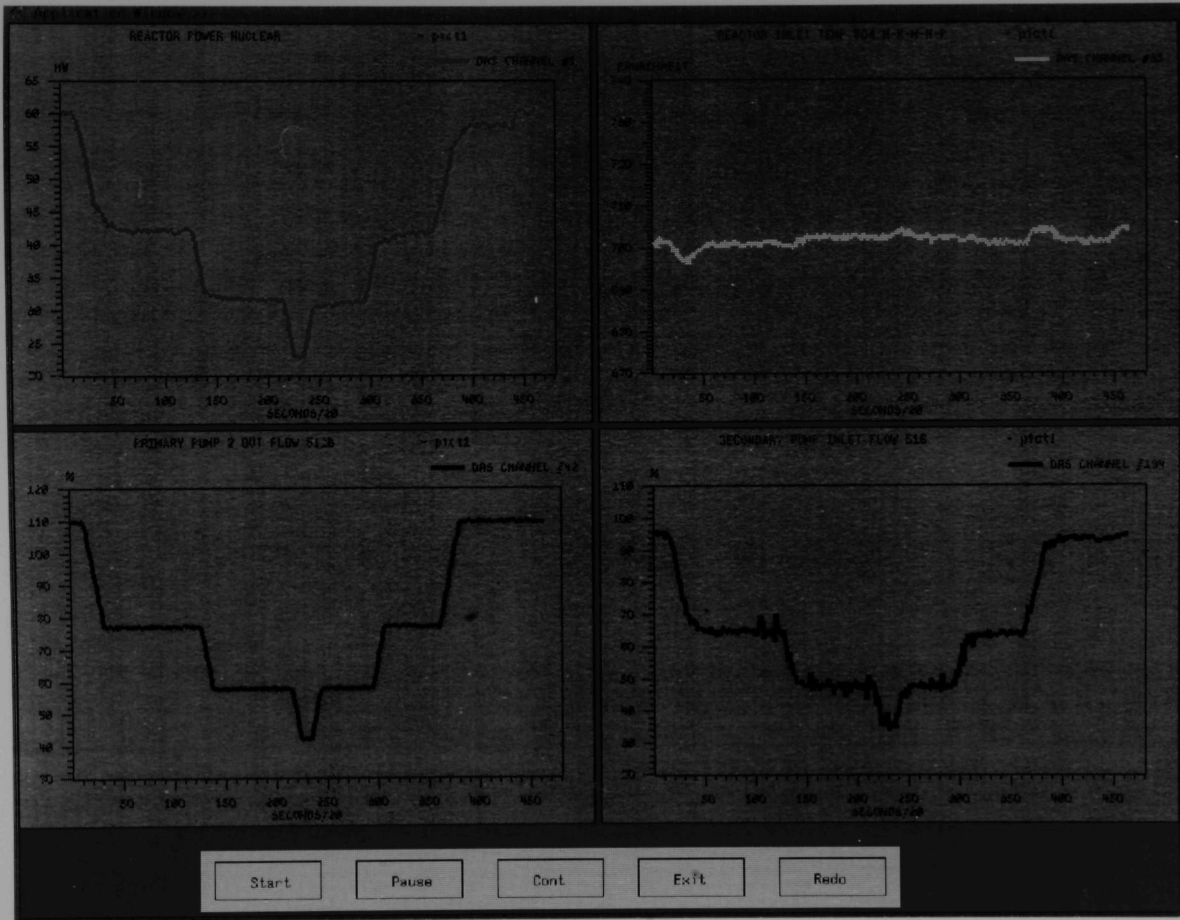
- Conclusion: Can vary power without rods by varying primary flow (in P/F term) and/or varying inlet temperature


THROTTLE VALVE
C4
T4
T6
P1
F3
TURBINE
GENERATO
CONDENSOR
SUPERHEATERS
PRESSURE REGULATING VALVE
C5
STEAM DRUM
FEEDWATER PUMP
EVAPORATORS
P2
T5
No. 4
No. 3
HEATERS
No. 2
No. 1
HEATERS
C2
C1
C2
T2
C3
T3
EM PUMP
F3
PUMP
CONTROL ROD
PUMP
F1
IHX
POW
REACTOR
T1
T1

PICT NO.1
PRIMARY FLOW CONTROL

TEST

- Control rods deenergized.
- Primary flow reduced from 110% to 42% in 3 steps and then returned to 110% in 3 steps.
- Reactivity feedback reduced power — nearly matched flow.
- Secondary flow was reduced to keep reactor inlet temperature constant.
- Electrical power follows the reactor power as the throttle is controlled to keep pressure constant.


REACTOR POWER NUCLEAR
MW
SECONDS/20
PRIMARY PUMP 2 OUT FLOW
%
SECONDS/20
SECONDARY PUMP INLET FLOW 516
%
SECONDS/20
Start
Pause
Cont
Exit
Redo

PICT 3 - CONTROL WITH SECONDARY FLOW/REACTOR INLET TEMPERATURE

Controller lineup

- Control rods — Deenergized
- Primary Pumps — Controlled to keep 100% flow
- Secondary Pumps — Controlling tank temperature on prescribed profile
- Turbine Throttle — Controlled to keep constant steam header pressure

Initial conditions

- 96% Power 60MW
- 96% Flow
- 680° F Tank temperature
- 1250 PSIG Steam header pressure

Test

- Secondary flow automatically controlled to increase tank temperature from 685°F to 725°F in 3 steps
- Reactivity feedback passively reduced reactor power from 60MW to about 30MW
- Changing secondary flow alters energy delivery rate to steam generator
- Steam power and electrical generation followed reactor power

PICT 4 CONTROL WITH TURBINE DEMAND

Controller Lineup

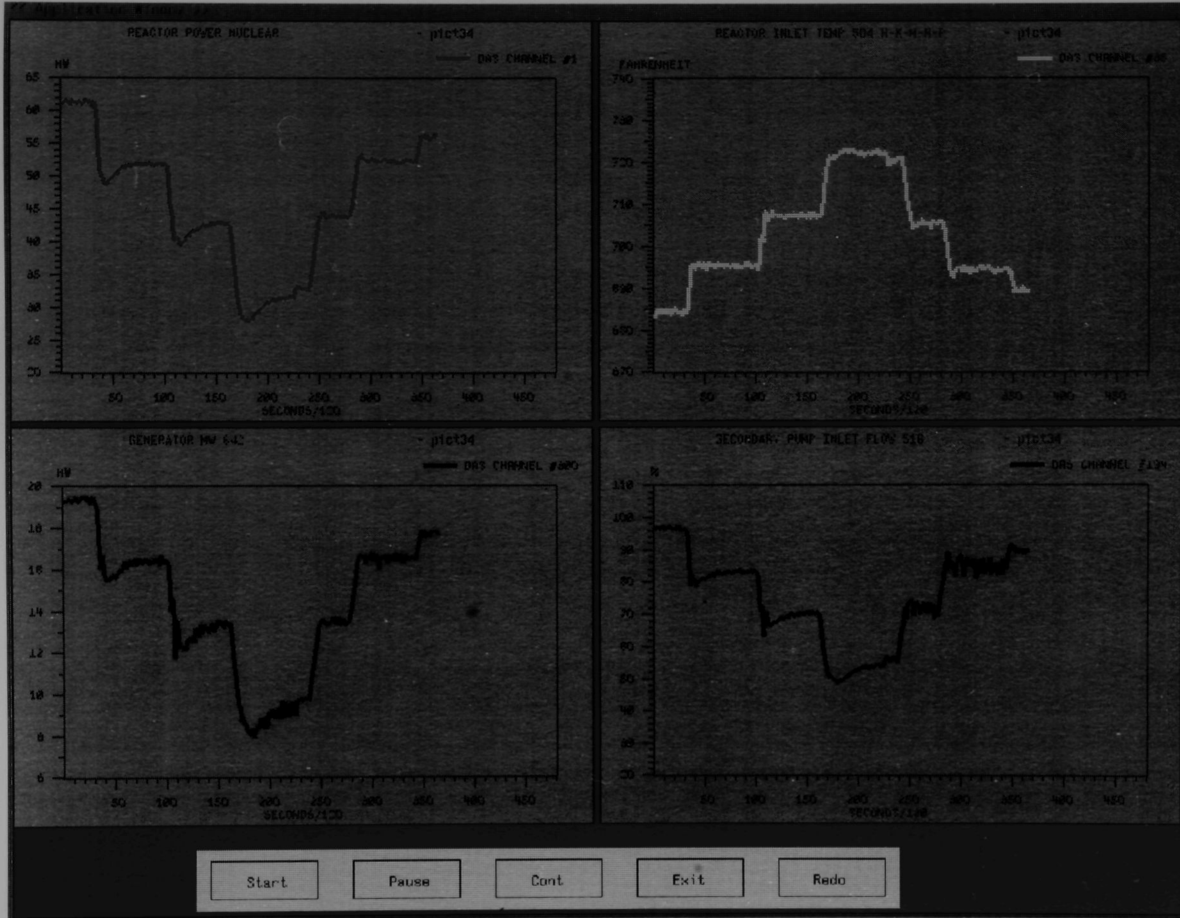
- Control rods — Deenergized
- Primary Pumps — Controlled to keep 100% flow
- Secondary pumps — Controlled to keep steam header pressure constant
- Turbine Throttle — Controlled to produce desired electrical output

Initial Conditions

- Final conditions of PICT 3 — About 50%

Test

- Controllers switched to above configuration (done from control room)
- Turbine controlled to ramp electrical output to values measured at each step in PICT 3
- Secondary Pump controlled to keep steam header pressure constant
- Increasing power demand resulted in cooling of reactor inlet temperature
- Reactor (responding to decreasing temperature) followed turbine power demand
- Reactivity loss from fuel depletion accommodated lower reactor inlet temperature


REACTOR POWER NUCLEAR - pict34
DAS CHANNEL #1
MW
REACTOR INLET TEMP 504
- pict34
FAHRENHEIT
GENERATOR MW 642 - pict34
MW
- pict34
%
Start
Pause
Cont
Exit
Redo

PICT 5 AND 6A TURBINE/STEAM PLANT CHARACTERIZATION

Controller lineup

- Control rods — Deenergized
- Primary pumps — Controlled to keep 100% flow
- Secondary pumps — Controlling steam pressure on a prescribed profile
- Turbine throttle — At fixed positions

Initial Conditions

- 96% Power 60MW
- 96% Flow
- 690°F Tank temperature
- 1250 psig steam header pressure

Test

- Secondary flow was controlled to reduce steam header pressure from 1250 to 800 psi in 3 steps
- Decreasing steam pressure decreased turbine generated power
- Concurrently decreasing the secondary flow increased the tank temperature and via reactivity feedbacks lowered the reactor power
- Throttle was opened full and pressure was increased in 3 steps to 995 psi (60MW)
- Turbine and steam plant operate well over the range from 800psig to1250psig

PICT 6B CONTROL WITH TURBINE DEMAND AND VARYING STEAM PRESSURE

Controller Lineup

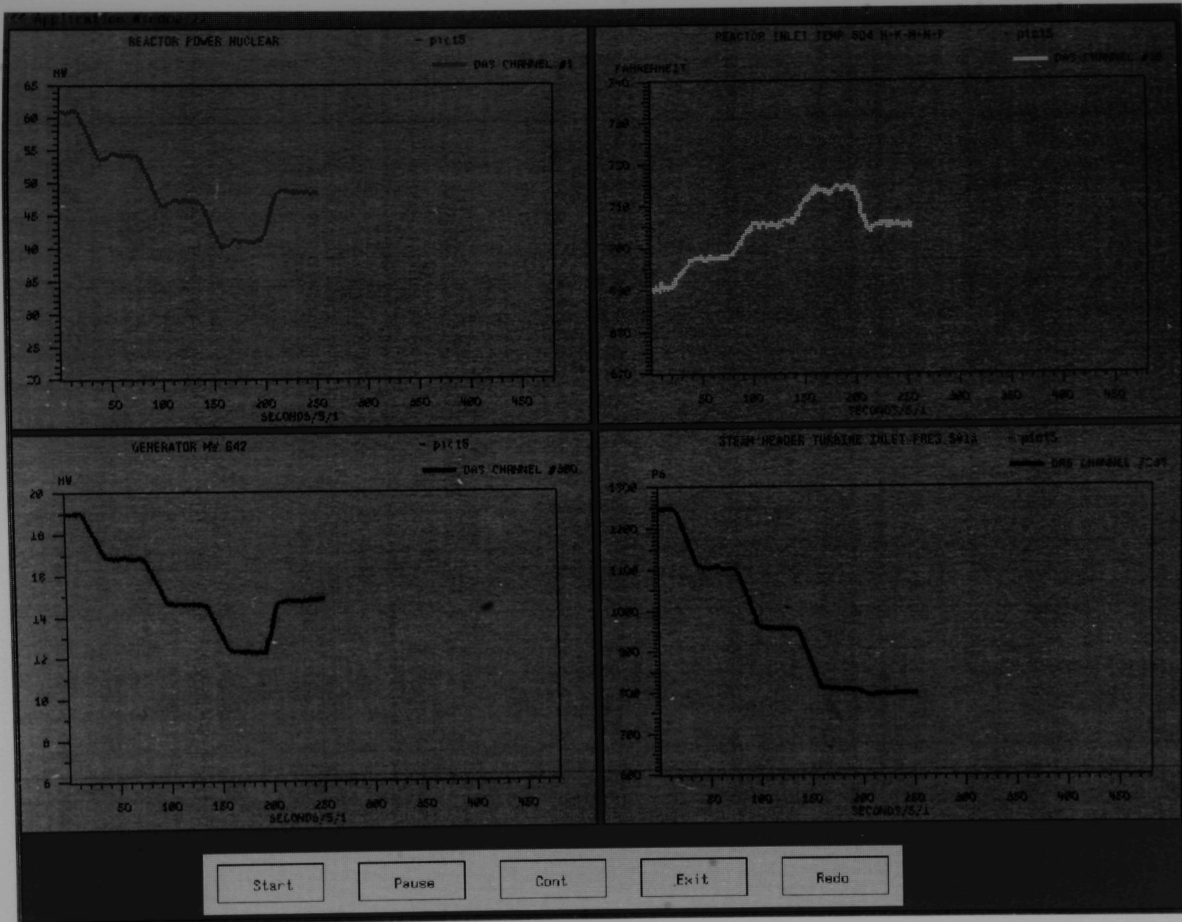
- Control rods — Deenergized
- Primary Pumps — Controlled to keep 96% flow
- Secondary Pumps — Controlling steam pressure on a prescribed profile
- Throttle Valve — Controlled to produce desired electrical output

Initial Conditions

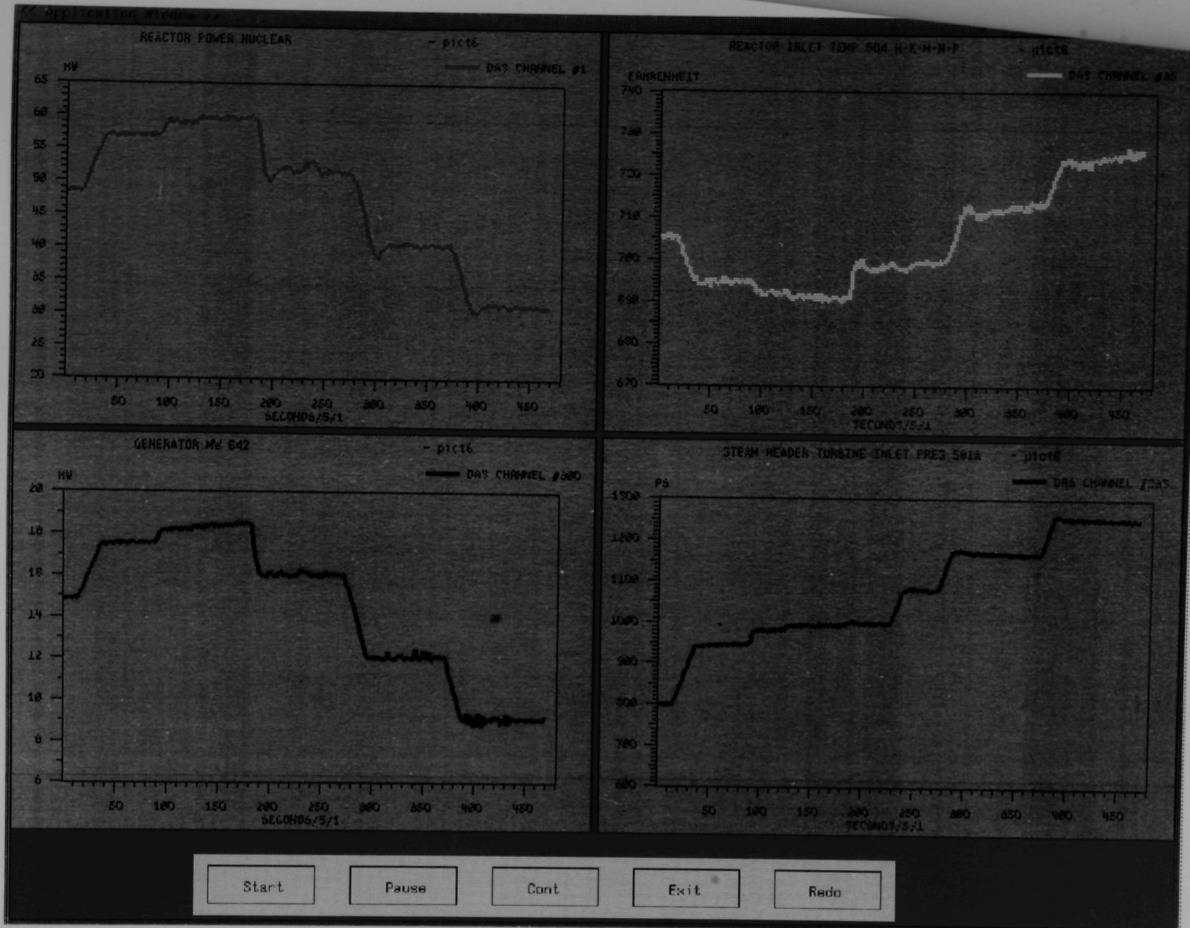
- Final conditions of PICT 6A — About 60MW reactor power and near minimum steam pressure for 60 MW

Test

- Turbine throttle controlled to decrease electrical output from 18.6MWe to 9MWe in 3 steps
- Secondary flow was controlled to increase steam pressure from 995 psi to 1250 psi in 3 corresponding steps
- Reactor followed turbine demand similar to PICT 3
- Increase of steam pressure raised steam saturation temperature and reactor inlet temperature and more directly coupled power demand to reactor



REACTOR POWER NUCLEAR
DAS CHANNEL #1
MW
SECONDS/5/1
FAHRENHEIT
GENERATOR MW
MW
Start
Pause
Cont
Exit
Redo


REACTOR POWER NUCLEAR
- pict6
MW
SECONDS/5/1
REACTOR INLET TEMP 504 H-K-M-N-P
- pict6
FAHRENHEIT
GENERATOR MW 642
- pict6
MW
SECONDS/5/1
STEAM HEADER TURBINE INLET PRES 501A
- pict6
PS
Start
Pause
Cont
Exit
Redo

CONCLUSIONS AND PROJECTIONS

- Reactor power controlled in "Load Following" maneuvers passively without control rods

- Control with Primary Pumps, Secondary Pumps and turbine throttle appears to be feasible

- The reactor and plant were stable and predictable during the tests

- Reactivity feedbacks associated with metal fuel are important in Passive Reactor Power Control

- Plant design — The sizing of pumps and heat exchangers can also be important to passive control

- Results suggest that several "closed loop" control schemes utilizing passive reactor control are possible

- Next steps
  —Develop and dynamically test alternate control schemes
  —Evaluate reliability and operational acceptability of control schemes
  —Evaluate and test inherently safe response of control schemes
  —Demonstrate inherent safety and reliability with tests

SUMMARY

J. I. Sackett
EBR-II Division

SUMMARY

- HAVE MADE SIGNIFICANT PROGRESS, DIRECT PAYOFFS BEGINNING TO BE FELT.

- WORK SHOULD FURTHER ENHANCE THE OPERATION AND SAFETY OF EBR-II

- A BASIC CONCEPT IS TO DEVELOP EBR-II AS A VERSATILE TEST BED, WITH WHICH WE CAN INVOLVE BOTH THE USER AND DEVELOPER COMMUNITIES IN WORK DIRECTED TO ADVANCED LMR DESIGN.

SUMMARY

EBR-II IS AN EFFECTIVE TEST BED FOR

1. DEVELOPMENT OF APPROACHES TO CONTROL WHICH CAN ACCOMMODATE CONTROLLER FAILURE WITHOUT ENDANGERING THE SAFETY OF THE REACTOR (E.G., DO NOT REQUIRE SAFETY-SYSTEM ACTION).

AND,

2. DEVELOPMENT OF DIAGNOSTIC AND CONTROL SYSTEM SOFTWARE TO SUPPORT INCREASINGLY SOPHISTICATED PLANT AUTOMATION IN BOTH LWRs AND LMRs.

TESTING ELEMENTS

I. CONTROL STRATEGIES

II. ADVANCED SIMULATION

III. DIAGNOSTICS

IV. PLANT AUTOMATION

V. COMPUTER RELIABILITY